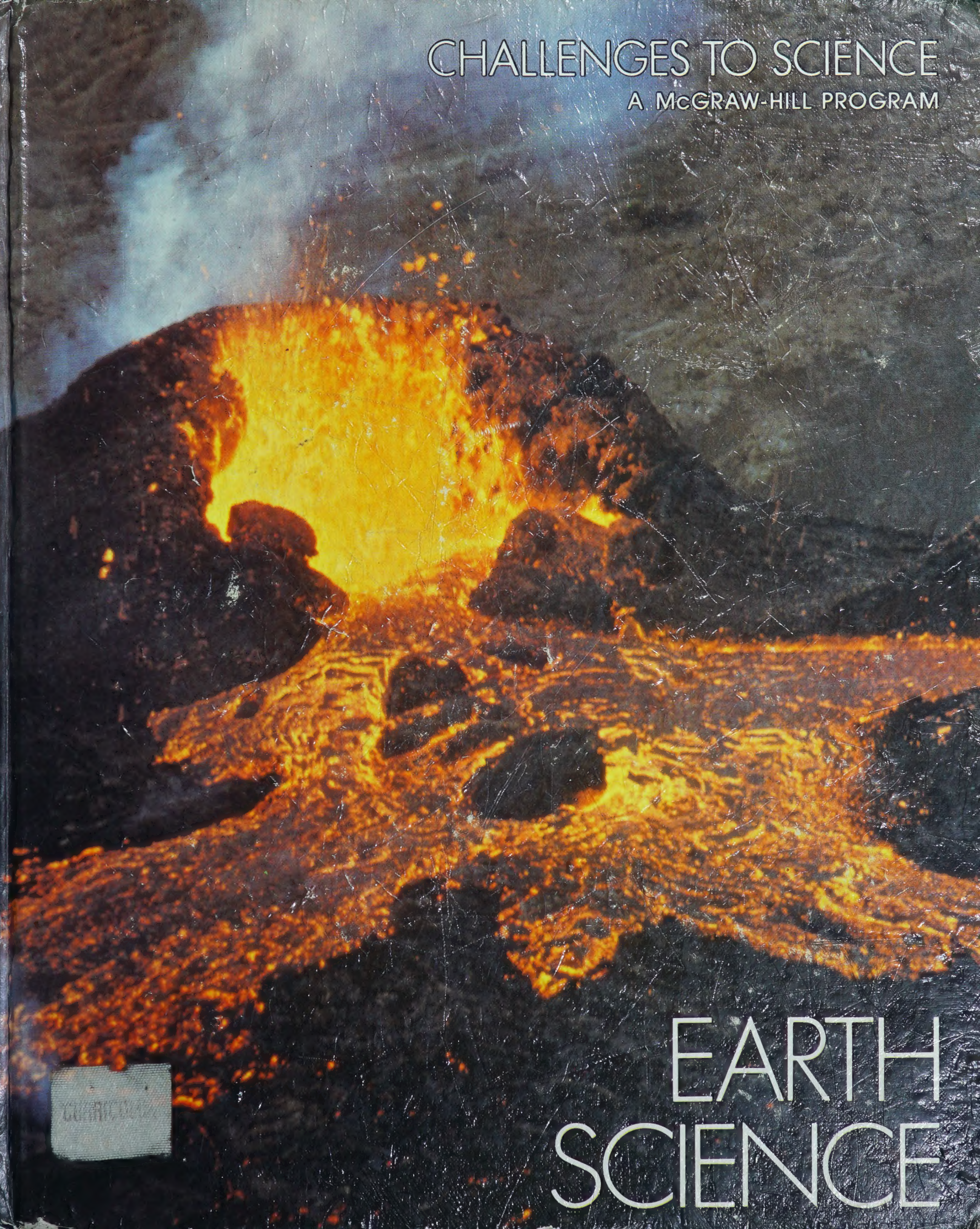

CHALLENGES TO SCIENCE

A McGRAW-HILL PROGRAM

EARTH SCIENCE

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Challenges to Science: Earth Science

By Robert Heller, John Byrne, David Darby, William Dexter, Bowman Hawkes, Karlis Kaufmanis, and Richard Ojakangas

Relates science to the needs of people.

Chapter 1	pp. 3–17	This book opens with a lively account of an astronaut from another solar system as he explores S_3 (the planet Earth, third from the Sun).
See Table of Contents See pages	 5, 224, 228, 309, 418	Students gain a better understanding of their world and what occurs around them as they study up-to-date earth science topics such as: sea-floor spreading, continental drift, and oceanography; solar wind, the magnetosphere, and other aspects of the Earth's nearby space environment; and astrophysical objects such as quasars, pulsars, neutron stars, and black holes.

Explores today's problems.

See pages	62, 77, 262, 299	Environmental awareness is emphasized throughout this text.
Chapter 13	pp. 263-281	In studying different world environments and man's energy needs, the student is asked to contrast nonindustrial man's primitive dwellings —which are generally comfortable because they take advantage of locations, wind direction, and the insulating qualities of natural materials —with city buildings which can be lived in only after enormous expenditure of energy for heating and cooling.

Leads students to discover concepts for themselves.

See pages	31–33, 117–121, 224–228, 322–323	Emphasis is on basic, meaningful concepts rather than on descriptive detail. Students can build much of the overall structure of science on their own, using the activities to fit the concepts into a pattern they can understand and remember.

Involves students actively in process-learning of science.

See pages	32–33, 118	Concepts are reinforced with process-oriented activities. Activities utilize simple, low-cost, easily-obtainable materials.
See pages	156–157	In exploring the environmental consequences of building a dam, the concept that a reservoir will eventually silt up and become unusable is illustrated in an activity with a miniature, homemade stream table.
See page	262	Students learn to analyze data—frequently presented in the form of pictures—and draw inferences.

Meets the need for a new kind of science education.

See Table of Contents		This text was written specifically for the interests and concerns of today's junior high school students. Reading level has been carefully controlled with little use of technical terminology, and there is a minimum use of mathematics.

CHALLENGES TO SCIENCE

Teacher's Edition

EARTH SCIENCE

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- Pupil's textbook
- Teacher edition
- Classroom kit
- Webstermaster tests
- Activity cards

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CONTENTS: TEACHER'S EDITION

Rationale

The purpose of this Teacher's Edition is to assist you, the teacher, in making your earth science class an exciting, challenging, process-oriented course that will help prepare your students to make wise decisions about their environment now and in the future. To accomplish this objective, a large amount of supplementary information has been included in the Teacher's Edition. This information can be found in two places: the annotations in the margins of the text pages and the additional enrichment in this tinted section. The annotations provide some in-depth material, suggestions on how to present parts of each chapter, and answers to any questions posed in the narrative of the text and captions as well as those at the end of each major section and chapter. These tinted pages contain general information in addition to lists of objectives, references, and audiovisual materials. This text was designed for a course presented through informal discussion and the investigation of basic ideas through simple activities. The interest evoked by the activities carries the student back into the text for reinforcement of his learnings and on into further activities.

The teacher demonstrations found at the beginning of each chapter are designed to generate student curiosity and interest in the subject matter of the chapter. These demonstrations should be set up in advance and be well rehearsed. If the demonstration consists of a film or filmstrip, this material should be carefully previewed. The demonstrations will help to get each chapter off to a running start because they are exciting and stimulating.

In EARTH SCIENCE, the process approach is used in an effort to emphasize basic principles and ideas. The vocabulary and narrative have been kept at an easy level. Several themes surface throughout the text with regularity:

Change is universal. Earth, all of its features, and all of its inhabitants are subject to constant change. Earth and the Universe of which it is a part are dynamic systems.

Energy is constantly being redistributed. Redistribution of energy from one system to another occurs both within Earth and at its surface. Oceans transfer thermal energy to the atmosphere and the atmosphere in turn transfers kinetic energy to the oceans.

Mass and energy are conserved. The total amount of matter and energy in the Universe remains constant. Transformation of matter to energy, energy to matter, and one form of energy to another occur; however, the sum of the two remains constant.

Natural systems tend to move toward a state of equilibrium. Equilibrium can be defined as a state of balance between opposing forces in an environment.

The present is a key to the past. Understanding the processes which now operate to modify Earth's surface, one can interpret Earth's history from the record left in rocks.

These five themes combine to offer students a clear understanding of, and respect for, the physical environment of Earth.

The efforts of the American Geological Institute to improve earth science teaching at the secondary school level resulted in the ESCP program and some fringe benefits as well. One of these benefits was the involvement of a large number of earth scientists, educators, and teachers, all helping to develop materials for use in secondary schools. This book is in part a result of this activity. Four of the authors (Byrne, Dexter, Hawkes, and Heller) of EARTH SCIENCE were involved with the Earth Science Curriculum Project as writers or administrators. The other three authors (Darby, Kaufmanis, and Ojakangas), although not directly associated with the project, were familiar with the material and approved of the general approach and philosophy used in them.

Suggestions for Directing Activities

The manner in which you, the teacher, guide the activities included in each chapter of this text is extremely important. The atmosphere in the classroom during the time that activities are being done should be conducive to inquiry and should foster the development of investigative attitudes and process skills. To accomplish these objectives, give your students as much freedom as possible—including the freedom to move about the room to confer with you and others. Above all, do not get alarmed if the noise level rises somewhat during an activity. If students get involved in and excited by an activity, there is bound to be an increase in noise.

The activities in EARTH SCIENCE can be conducted in almost any kind of classroom, no matter how poorly equipped. Only a minimum amount of space and equipment is needed for each activity. Materials and equipment needed for each activity are listed in the chapter discussions.

Before your students work on an activity, you will find it both helpful and rewarding to prepare yourself. Perform the activity yourself and try to identify questions that students might ask. Do necessary background reading to enable you to answer probable questions. Pre- and post-activity

discussions will be quite fruitful in promoting understanding of the concepts studied. Make sure that you have an adequate supply of all materials and equipment before your class arrives. If an activity involves movement of students from one station to another, plan a traffic pattern that will result in as little congestion as possible. *Alert students to any safety precautions they should take in doing the activity.* Specific warnings are given in the text whenever appropriate. However, teachers should provide informed supervision at all times. An excellent reference on the subject is published by the New York City Board of Education. This pamphlet, *For Science Safety in Grades K-12 in Science Teaching*, should be part of the personal library of every science teacher. It can be obtained by sending $1 to the New York City Board of Education, Publication Sales, 110 Livingston Street, Brooklyn, New York 11201.

One of the basic objectives of each activity is to have students learn by doing. In doing, they will inevitably make mistakes. This is not as bad as it may sound, however. Scientists learn from making mistakes and so can students. Take advantage of any mistakes that students make by helping them recognize their problems. They can then find solutions themselves.

To ensure that every student is involved in doing each activity, groupings should be kept as small as possible. Space and equipment limitations might make small grouping impossible for certain activities. However, keep in mind that the larger the groups, the less likely it is that all students will be actively involved.

Apparatus List for Year's Work

Quantities are generally based on a class size of 28 with students working in groups of 4.

Balls, tennis	14
Beakers, glass, 500-ml	21
Binoculars	as many as convenient, up to 7, stagger use
Blowpipes	7
Blowpipe rests	7
Bottles, small, with caps	7
Bunsen burners	7
Compasses, drawing	7
Containers, rectangular, glass or plastic, with open top (15 to 20 cm long, 10 to 15 cm wide and 5 to 10 cm high)	14
Crucibles, porcelain	7
Cylinders, 100-ml graduated	7
Cylinders, large-diameter graduated, 1000 ml	7
Cylinders, tall, graduated, glass, 1000 ml	7
Flashlights	7
Flasks, 500-ml OR pint bottles with cover	7
Forceps	10
Football field	1 (reserve use with the Physical Education Department of your school or of a school in the vicinity)
Hammers	7
Hoses, flexible rubber, siphon ($\frac{1}{2}$-cm diameter, at least 1 m long)	14 pieces
Hot plates	as many as convenient, up to 7, stagger use
Jugs, heavy glass, 1-gal with cap	7
Lamp, mercury	1
Lamp, neon	1
Magnifying glasses	7
Medicine droppers	7
Meter sticks	7
Microscopes, binocular	as many as convenient, up to 7, stagger use
Pails, standard scrub	7
Pans, large sheet cake, glass	7
Pans, pie, with sloping sides	7
Pans, Pyrex meatloaf, with sloping sides (use ordinary loaf pans)	7
Petri dishes	7

Prisms, glass	7
Projection screen	1 (reserve use)
Projector	1 (reserve use)
Protractors	7
Ring stands with clamps OR tripods	7
Refrigerator	1 (reserve use with Home Economics Department)
Rulers, 30-cm	7
Scales, laboratory (platform or triple-beam)	as many as convenient, up to 7, stagger use
Scissors	7
Table, large OR classroom floor	as many as convenient in space allowed, stagger use
Telescopes, small	as many as convenient, up to 7, stagger use
Triangles, clay OR wire gauze squares	7
Troughs, open, plastic, metal, or glass about 1 m long and 2 to 10 cm wide (can be made of sheet metal)	7
Tubes, cardboard or metal (15 to 25 cm long, 5 cm in diameter)	7
Tuning forks, high-pitched	as many as convenient, up to 7, stagger use
Watch OR clock, with second hand	as many as convenient, up to 7, stagger use

Materials List for Year's Work

Quantities are generally based on a class size of 28 with students working in groups of 4.

Blocks, charcoal	7
Blocks, wood (4 to 9 cm wide, 4 to 9 cm high, 5 cm long)	14
5 cm x 10 cm x 15 mm thick	7
5 cm x 10 cm x 25 mm thick	7
5 cm x 10 cm x 40 mm thick	7
Books, heavy	10
Boxes, cardboard (20 to 50 cm on a side)	7
Boxes, florist's long, cardboard (about 60 cm long)	7
Boxes, cardboard shoe boxes with removable tops	7
Boxes, cardboard, small, various heights	30
Cardboard	class supply
Clay, modeling (nonhardening)	7 pounds of one color 14 pounds of a second color
Corks	2 dozen
Diffraction gratings, plastic	10
Feldspar	1 pound (2 cm x 2 cm x 2 cm pieces)
Galena	2 pounds
Glue	class supply
Halite	2 pounds
Igneous rock specimens	1 pound
Ink OR food coloring	1 bottle
Iron sulfate	1 pound
Lubricant, Vaseline, or other type	medium-sized jar
Marbles, average size	700
Paper, writing	class supply
Paper, black construction	20 sheets
Paper, graph	class supply
Paper, graph, large sheets, rectangular	class supply

Paper, tracing	class supply
Pencils	class supply
Pyrite (FeS_2) (2-cm x 2-cm x 2-cm pieces)	5 pounds
Quartz (2-cm x 2-cm x 2-cm pieces)	1 pound
Rods, long, thin (knitting needles, pencils, or drinking straws may be used)	30 pieces
Rocks, to use as weights for pieces of paper	63
Salt, table	1 box
Sand, light-colored	5 pounds
Sediment, consisting of clay, silt, and sand	10 to 15 pounds
Sediment, consisting of clay, silt, fine sand, coarse sand, and small pebbles)	15 pebbles
Shot, fine lead or copper	20 pounds
Silly Putty	7 containers
Tape, adding machine	5 rolls
Tape, adhesive	1 roll
Tape, transparent	class roll
Thymol	$\frac{1}{4}$ pound
Water, lake or river	to be collected in a bottle by each group of students

Ice cubes are used in a few of the activities; be sure that there is a source at hand.
Tap water should be readily available.

Recommended Time Schedule for EARTH SCIENCE

The following recommendation is based on a 36-week school term. Adjustments should be made accordingly for shorter or longer terms.

In order to complete the textbook, it is suggested that this schedule be followed.

The first 9-week period (first quarter) allows the completion of the text section on rocks—Chapters 1 through 5. These five chapters include many activities, and we feel that during the first 9 weeks students are more eager and ambitious than they will be later and will find this section exciting.

The second 9-week period should begin with Chapter 6 and end with Chapter 9—a long chapter—perhaps the most interesting section for many Earth Science students.

The third 9-week section should begin with Chapter 10 and end with Chapter 15.

The last unit—Unit IV—will begin with the fourth 9-week period. Chapter 20 should be completed during the last weeks of school. This last unit will also be very exciting for many students, even though student interest and ambition usually taper off at this time.

Chapter 1	1 week	Chapter 10	2 weeks
Chapter 2	2 weeks	Chapter 11	1 week
Chapter 3	2 weeks	Chapter 12	2 weeks
Chapter 4	2 weeks	Chapter 13	1 week
Chapter 5	2 weeks	Chapter 14	1 week
		Chapter 15	2 weeks
Chapter 6	3 weeks	Chapter 16	2 weeks
Chapter 7	1 week	Chapter 17	1 week
Chapter 8	2 weeks	Chapter 18	2 weeks
Chapter 9	3 weeks	Chapter 19	2 weeks
		Chapter 20	2 weeks

We realize that this is not an ideal schedule for every situation. We do feel that teachers should develop a teaching schedule and try to maintain it in order to avoid the omission of important material.

Chapter 1

OBJECTIVES

1. Students will see the world rather than notice it.
2. Students will question Earth as if they had never seen it, thereby becoming able to analyze what makes it unique.
3. Students will be able to use their powers of observation to perceive the wonders around them.

Comments

page 3
(1) The objective of Chapter 1 is a very simple yet difficult one. It is to make students *see* the world instead of merely *noticing* it. Having been raised on Earth, we all tend to accept our surroundings with the same casual unconcern with which we accept our ability to see or hear. One blade of grass on the Moon would cause a scientific uproar, yet the

thousands of kinds of grass on Earth, from bamboo to crab grass, startle almost no one. Animals and air, rocks, water, and warmth—all are simply accepted. But, if your students can be led to question Earth as though they were explorers, perhaps they can begin to see its marvels. To do this involves a change in the way they use their minds and eyes. It is simple to start such thinking, but difficult to become practiced at it. For example, if there is a hill visible from the classroom, why is it there? And if there is no hill, why isn't there?

These questions are typical of those that a small child asks his parents. The small child is the true explorer, but unfortunately children stop wondering very early, especially if they are ignored. The geologist (or other scientist) must redevelop this attitude of questioning (seeing) and it requires a self-discipline that not all who try can achieve. If you can ask the "childish" questions—Why don't birds have teeth? Where does dirt come from? Where does the Moon go during the day? What about that hill out the window?—then perhaps your students, in trying to answer, can find a closer relationship with the Earth explorers in Chapter 1.

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Fraser, Ronald G. J., *The Habitable Earth*, Basic Books, New York, 1965.
Gamow, George, *Biography of the Earth: Its Past, Present, and Future*, New American Library, New York, 1960.
Gamow, George, *A Planet Called Earth*, Viking, New York, 1963.
Spilhaus, Athelstan, *Satellite of the Sun*, Viking, 1962.
Stumpf, Karl, *Planet Earth*, University of Michigan Press, Ann Arbor, 1960.

AUDIOVISUAL MATERIALS

FILM
The View from Space (M-H)

FILMSTRIPS
The Earth Beneath Us (M-H)
The Earth Science (M-H)

Chapter 2

OBJECTIVES

1. Students will be able to state how matter (Earth materials) is constituted—the makeup of atoms, minerals, and rocks.
2. Students will be able to name the main elements present in Earth's crust, especially the three most abundant ones.
3. Students will have a reasonably good understanding of how ions are bonded together to make minerals and how the internal arrangements of ions influence the physical properties of minerals.
4. Students will understand, in a preliminary way at this point, how rocks are related to each other in the rock cycle.
5. Students will understand the meaning of uniformitarianism: The present is the key to the past.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 2.1
Table salt
Halite
Magnifying glass

Activity 2.2
Cardboard
Transparent tape

REFERENCES

Holden, Alan, and Singer, P., *Crystals and Crystal Growing*, Doubleday, New York, 1960 (paperback).
Hurlbut, C. S., Jr., *Dana's Manual of Minerology* (any ed.), Wiley, New York, 1959 (or more recent).
Pearl, Richard M., *Rocks and Minerals*, Barnes and Noble, New York, 1956.
Pough, Frederick H., *A Field Guide to Rocks and Minerals* (3d ed.), Houghton Mifflin, Boston, 1960.
Vanders, Iris, and Kerr, Paul F., *Mineral Recognition*, Wiley, New York, 1967.

AUDIOVISUAL MATERIALS

FILM
Crystals—An Introduction (BT)

FILMSTRIPS
Recognizing Rock-Making Minerals (EBEC)
Comparing Rocks (EBEC)
Rocks and the Landscape (EBEC)
Minerals and Rocks (M-H)

Chapter 3

OBJECTIVES

1. Students will be able to distinguish between extrusive and intrusive igneous rocks on the basis of texture and to give a brief history of cooling for each kind of rock.
2. Students will be able to discuss how different kinds of magma might originate.
3. Students will know and be able to recognize the types of igneous rocks and realize that granitic and basaltic rocks constitute most of the igneous rocks of Earth's crust.
4. Students will be able to name some major valuable igneous mineral deposits.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 3.1
Thymol
A Petri dish
A hot plate
Microscope (preferably a binocular microscope)
Forceps

Activity 3.2
Igneous rock specimens

Activity 3.3
Galena
Porcelain crucible
Ring stand OR tripod
Clay triangle OR wire gauze square
Bunsen burner
Charcoal block
Blowpipe
Blowpipe rest

AUDIOVISUAL MATERIALS

FILM
Rocks That Originate Underground (EBEC)

FILMSTRIPS
Volcanic Rocks (EBEC)
Plutonic Rocks (EBEC)

FILM LOOP
Igneous Processes (M-H)

Chapter 4

OBJECTIVES

1. Students will appreciate the statement, "Minerals are stable only in the environment in which they formed." They will then better understand why rocks and minerals are weathered at Earth's surface.
2. Students will understand the differences between mechanical and chemical weathering and their interrelationships. They will also know how soil is formed and why it must be conserved.
3. Students will understand how loose sediment is moved, deposited, and transformed into sedimentary rock. They will also appreciate how geologists use sedimentary features, mineralogy, and texture to interpret the history of a sedimentary rock.
4. Students will know the principal types of sedimentary rocks and the most important sedimentary mineral resources.
5. Students will realize and understand why geologists of the past thought in terms of "layer-cake" geology rather than in terms of sedimentary facies.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 4.1
Paper
Pencil

Activity 4.2
Iron sulfate
500-ml flask OR pint bottle with cover
Water

Activity 4.3
Heavy glass gallon jug with cap
Tall graduated glass cylinder
Watch OR clock with second hand
Sediment

Activity 4.4
Bottles for collecting water
Lake or river water

Activity 4.5
Pencil
Paper

Activity 4.6
Pie pan with sloping sides
Light-colored sand
Pyrite (FeS_2)
Galena (PbS)
Quartz
Feldspar

Activity 4.7
Quartz
Pyrite
Galena
Feldspar

Large-diameter graduated cylinder
Water
Laboratory scale

REFERENCES

Sedimentation:

Harbaugh, John W., *Stratigraphy and Geologic Time*, Chapter 5, Wm. C. Brown, Dubuque, Iowa, 1968.

Krumbein, W. C., and Sloss, L. L., *Stratigraphy and Sedimentation* (2d ed.), Chapters 4-7, W. H. Freeman, San Francisco, 1963.

Shrock, R., *Sequence in Layered Rocks*, McGraw-Hill, New York, 1948.

Twenhofel, W. H., *Principles of Sedimentation* (2d ed.), Chapters I-IV, McGraw-Hill, New York, 1950.

Stratigraphy:

Dunbar, Carl O., and Rogers, John, *Principles of Stratigraphy*, Wiley, New York, 1957.

Harbaugh, John W., *Stratigraphy and Geologic Time*, Chapters 2 and 3, Wm. C. Brown, Dubuque, Iowa, 1968.

Krumbein, W. C., and Sloss, L. L., *Stratigraphy and Sedimentation* (2d ed.), Chapters 1-3, 8-10, 13, W. H. Freeman, San Francisco, 1963.

AUDIOVISUAL MATERIALS

FILMS

Rocks That Form on the Earth's Surface (EBEC)
The Beach—A River of Sand (EBEC)

FILMSTRIP

Sedimentary Rocks (W)

FILM LOOP

Sediments and Sedimentary Rocks (M-H)

Chapter 5

OBJECTIVES

1. Students will further appreciate the statement, "Minerals are stable only in the environment in which they formed." They will then understand why rocks and minerals are changed to other rocks and minerals under different conditions of temperature, pressure, and chemical surroundings.
2. Students will know why the most abundant metamorphic minerals are also the most abundant igneous minerals.
3. Students will understand the difficulties in studying metamorphism, since it occurs at depth and is not observable.
4. Students will know the main metamorphic rock types mentioned and know that each was originally another type of rock.

AUDIOVISUAL MATERIALS

FILMSTRIPS

Coal (EBEC)
Coal—A Fossil Fuel (POPSCI)

FILM LOOP

Metamorphism and Coal Formation (M-H)

Chapter 6

OBJECTIVES

1. Students will be able to name and describe the three main types of volcanoes; they will also be able to describe basalt floods.
2. Students will be able to name advantages and disadvantages of living in a volcanically active area.
3. Students will understand the causes of earthquakes, means of detecting them, and their predictability.
4. Students will understand the model of Earth's interior and how scientists arrived at this model.
5. Students will know where the active volcanic and earthquake zones are located.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 6.1
Ring stand with clamps
Cardboard box
Paper
Pencils

Activity 6.2
Ice cubes
Blocks of wood
Clear plastic container
Ruler, 30-cm

REFERENCES

Anderson, Don L., "The Plastic Layer of the Earth's Mantle," *Scientific American*, July 1962, or offprint no. 855, W. H. Freeman, San Francisco.

Bullen, K. E., "The Interior of the Earth," *Scientific American*, September 1955, or offprint no. 804, W. H. Freeman, San Francisco.

Bullard, Fred M., *Volcanoes: In History, In Theory, In Eruption*, University of Texas Press, Austin, 1962.

Grantz, Arthur, Plafker, George, and Kachadoorian, Roubon, *Alaska's Good Friday Earthquake, March 27, 1964*, U.S.G.S. Circ. 491, 1964.

Jacobs, J. A., *The Earth's Core and Geomagnetism*, Pergamon-MacMillan, New York, 1963 (paperback).

Jacobs, J. A., Russell, R. D., and Wilson, J. Tuzo, *Physics and Geology*, McGraw-Hill, New York, 1959.

Moore, James G., Kazauki, Nakamura, and Alcaraz, Arturo, "The 1965 Eruption of Taal Volcano," *Science*, February 25, 1966, pp. 955-960.

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Waesche, Hugh H., and Peck, Dallas L., "Volcanoes Tell Secrets in Hawaii," *Natural History*, March 1966, pp. 21-29.

Williams, Howel, "Volcanoes" *Scientific American*, November 1951, or offprint no. 822, W. H. Freeman, San Francisco.

AUDIOVISUAL MATERIALS

FILMS

Case History of a Volcano (PRISM)
Eruption of Kilauea (USDA)
The Earth—Changes in its Surface (CORF)
Volcanoes on Earth (EBEC)
The Hidden Earth (M-H)
Volcano (UCB)
Volcanic Violence (FILMS)

FILMSTRIPS

Work of Internal Forces (HB)
Volcanoes (W)
Volcanoes (IMPRL)
Volcanoes and Earthquakes (POPSCI)
Volcanoes (HB)

FILM LOOP

Volcanoes (EAL)

Chapter 7

OBJECTIVES

1. Students will understand the processes of folding and faulting and be able to appreciate in a general way the forces that produced them.
2. Students will understand the significance of buried surfaces of erosion and be able to read some Earth history from them.
3. Students will understand, in a general way, the theories explaining the origins of the large folded mountain belts of the world.
4. Students should realize that whereas volcanoes and earthquakes occur suddenly, the processes of folding, mountain building, uplift, and erosion proceed slowly.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 7.1
Silly Putty
Hammers
Heavy books
Refrigerator

Activity 7.2
Modeling clay, 2 colors
Rectangular plastic or glass container with open top
Block of wood
Vaseline or other lubricant

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Beloussov, V. V., "Experimental Geology," *Scientific American*, February 1961, pp. 97-106.

Calder, Nigel, *The Restless Earth*, Viking, New York, 1972.

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Wilson, J. Tuzo, "Continental Drift," *Scientific American*, April 1963, or offprint no. 868, W. H. Freeman, San Francisco.

Continents Adrift, Readings from *Scientific American*, W. H. Freeman, San Francisco, 1972.

The San Andreas Fault, U.S.G.S. Leaflet

AUDIOVISUAL MATERIALS

FILMS

How Solid Is Rock? (EBEC)
Face of the Earth (EBEC)
Hidden Earth (M-H)

FILMSTRIP

Earth Cycles and Changes (M-H)

FILM LOOP

Glaciation (M-H)

GEOLOGIC MAPS

Information concerning availability of published geologic maps for your local area usually can be obtained from the list of publications issued by the geological survey of your state.

Listed below are several geologic maps which illustrate a variety of geologic features. These are colored geologic maps with a brief accompanying text. They are available at nominal cost from the U. S. Geological Survey. A more complete list of geologic maps can be found in "Publications of the Geological Survey," available free on request from the U.S. Geological Survey, Washington, D.C. 20242. The selected maps and the type of geologic conditions they depict are:

Cave Terrain: GQ98, Carlsbad Caverns East, by P. T. Hayes and B. T. Gale, 1957.

Faulting: GQ50, Valyermo, Calif., by L. F. Noble, 1954. GQ128, Haunted Canyon, Ariz., by D. W. Peterson, 1960.

Flat and Gently Dipping Beds: In an area of low relief—GQ113, Epes, Alabama, by W. H. Monroe and J. L. Hunt, 1958. GQ49, Fredonia, Kans., by H. C. Wagner, 1954. In an area of high relief—GQ72, Paradox, Colo., by C. F. Withington, 1955. GQ81, Juanita Arch, Colo., by E. M. Shoemaker, 1955.

Folded Beds: In an area of low relief—GQ115, Knoxville, Tenn., by J. M. Cattermole, 1958. In an area of high relief—GQ109, Bedford, Wyoming, by W. W. Rubey, 1958.

Geologic Map Symbols, Data Sheets 1, 2, and 3 available at reduced price in quantities of 10 or more sets. Data Sheet 20 deals with fault symbols. Available from American Geological Institute.

Glacial Terrain: GQ119, New Britain, Conn., H. E. Simpson, 1959.

Igneous Rocks: Batholithic—GQ99, Casa Diablo Mountain, Calif., by C. D. Rinehart and D. C. Ross, 1957. Volcanic—GQ48, Hay, Washington, by H. H. Waldron and L. M. Gard, Jr., 1954. Dikes and Sills—GQ103, Golden, Colo., by Richard Van Horn, 1957.

Chapter 8

OBJECTIVES

1. Students will know the principal agents of leveling—running water, underground water, glaciers, and wind—and realize that all are acting under the influence of gravity.
2. Students will understand how each of the agents in Objective 1 operates and should be able to recognize which agent in a given area has had the most influence on the landscape. They will know that each agent erodes and each deposits, with characteristic results.
3. Students will appreciate that changes are constantly going on all around us, but at rates that are commonly so slow that the changes are hardly noticeable. They will be able to recognize and point out several processes of change.
4. Students will be able to point out numerous changes in the landscape, and in our environment in general, that have been caused by man.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 8.1

Open trough
Pail
Siphon hose
Stopwatch or watch with second hand
Piece of cork
Ruler
Graph paper
Cardboard boxes, small
Blocks

Activity 8.2

Sediment
Flat, glass sheet cake pan
Modeling clay
Water
Siphon hose

Activity 8.3

3 500-ml glass beakers
100-ml graduated cylinder
Marbles, average size
Fine lead or copper shot
Sand

REFERENCES

Dyson, J. L., *The World of Ice*, Knopf, New York, 1962.

Earth Science Curriculum Project; *Investigating the Earth*, Houghton Mifflin, Boston, 1967.

Flint, R. F., *Glacial and Pleistocene Geology*, Wiley, New York, 1957.

Gilluly, J., Waters, A. C., and Woodford, A. O., *Principles of Geology*, W. H. Freeman, San Francisco, 1959.

Keller, W. D., *Principles of Chemical Weathering* (rev. ed.), Lucas Brothers, Columbia, Missouri, 1957.

Kellogg, C. E., "Soil," *Scientific American*, July, 1950.

Leet, L. D., and Judson, S., *Physical Geology* (3d ed.), Prentice-Hall, Englewood Cliffs, New Jersey, 1965.

Ley, Willy, *The Poles*, Life Nature Library Series, Time, Inc., New York, 1962.

Mather, Kirtley F., *The Earth Beneath Us: the Fascinating Story of Geology*, Random House, New York, 1964.

Millar, C. E., Turk, L. M., and Foth, H. D., *Fundamentals of Soil Science* (4th ed.), Wiley, New York, 1965.

Ramsey, W. L., and Burckley, R. A., *Modern Earth Science* (2d ed.), Holt, New York, 1968.

Scovel, J. L., et al., *Atlas of Landforms*, Wiley, New York, 1965.

Shelton, J. S., *Geology Illustrated*, W. H. Freeman, San Francisco, 1966.

Shimer, J. A., *This Sculptured Earth: the Landscape of America*, Columbia University Press, New York, 1959.

Schultz, Gwen, *Glaciers and the Ice Age*, Holt, New York, 1965.

Strahler, A. N., *Introduction to Physical Geography*, Wiley, New York, 1965.

AUDIOVISUAL MATERIALS

FILMS

Why Do We Still Have Mountains (EBEC)
Erosion—Leveling the Land (EBEC)
Evidence for the Ice Age (EBEC)
Understanding Our Earth: Soil (CORF)
Face of the Earth (EBEC)
Geological Work of Ice (EBEC)
The Great Lakes—How They Were Formed (EBEC)
Understanding Our Earth: Glaciers (CORF)
Continental Glaciers (OSUMPD)

FILMSTRIPS

Work of Running Water (HB)
Work of Wind (HB)
Work of Ground Water (HB)
Work of Snow and Ice (HB)
Investigating a Glacier (EBEC)
How a Glacier Shapes Its Valley (EBEC)
Reconstructing the Ice Age (EBEC)
Some Side Effects of the Ice Age (EBEC)

FILM LOOP

Wind Erosion and Deposition (M-H)

Chapter 9

OBJECTIVES

1. The student will be able to understand why the age of Earth has to be very great and to explain how the age of rocks is measured.
2. The student will appreciate that it took a very long time to make things as they are, but that man's carelessness with natural resources—wood, fossil fuels, and so on—may quickly ruin the work of millennia.
3. The student will be able to discuss the temporal nature of landforms and life-forms, as they now look.

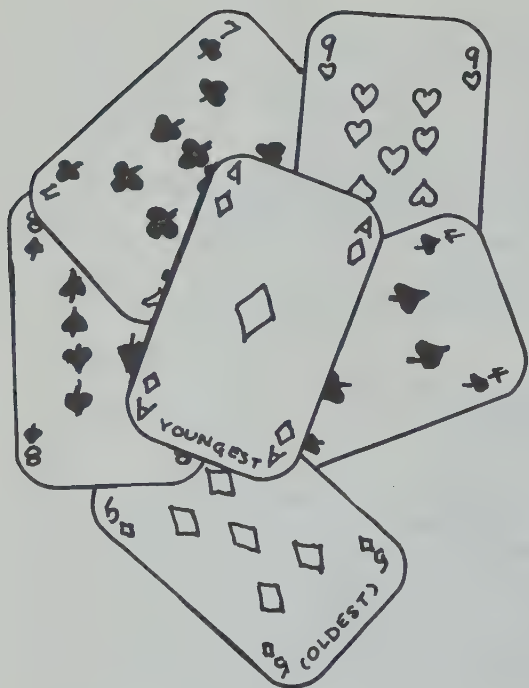
Comments

Introductory demonstration, continued

page 171

You can now use two decks of cards to illustrate superposition and correlation. After your students have tried to work out ways of determining relative ages of rock layers, you can toss a set of six cards one by one onto a table in the following order, for example: five of diamonds, eight of spades, seven of clubs, nine of hearts, four of spades, and ace of diamonds. The idea of sedimentary layers horizontally accumulating over many years in the same order, one on top of another, is then demonstrated. In the pile of cards, the five of diamonds is the oldest card, and the ace of diamonds the youngest. The same principle applies to layers of rock.

From another deck, toss a second pile in the following order: seven of clubs, nine of hearts, four of spades, ace of diamonds, ten of spades, and two of clubs. Your students can then correlate the two piles, since the ace, nine, four, and seven match; they can then get the idea that the last two cards in the second pile are even younger than the ace atop the first pile. You can then put forth the idea that



PILE 1

PILE 2

the second pile represents an exposure of rock layers 50 kilometers or so away from the first.

You can speculate about what happened to the rock layers represented by the ten of spades and two of clubs at outcrop (card pile) number one. Were they never deposited there, or were they worn off? You could even show near-vertical layers of rock on a 35-mm slide and ask your students how they could tell if "up" is to the left or right when the second pile is held on edge. By knowing the age relation of pile one, they can grasp that "up" for the second pile has been *visually* altered by the folding and tilting of the rock layers.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 9.1
Pencil
Paper

Activity 9.2
Adding machine tape
Meter sticks

REFERENCES
Hurley, P. M., *How Old is the Earth?* Doubleday, Garden City, N.Y., 1959 (paperback).
Mac Fall, Russell P., and Wollen, Jay, *Fossils for Amateurs: a Handbook for Collectors,* Van Nostrand Reinhold, New York, 1972.
McAlester, A. L., *The History of Life*, Prentice-Hall, Englewood Cliffs, N.J., 1968.

AUDIOVISUAL MATERIALS

FILMS
The Fossil Story (SOC)
Hunting Animals of the Past (UNEBR)
The Earth in Change—The Earth's Crust (EBEC)

Chapter 10

OBJECTIVES

1. Students will be able to describe the difference in construction of maps of land surfaces and of the sea floor. They will be able to explain how we learn of the shapes of sea-floor features and why these features differ in size and character from those

occurring on land. Students will also be able to demonstrate a knowledge of the indirect methods of obtaining depth measurements.
2. Students will have a knowledge of the shape and origin of the major features of the sea floor. They will be able to demonstrate the importance of the continental shelf to the wellbeing of their own and other countries. They will be able to demonstrate a knowledge of the differences between continental portions and oceanic portions of Earth's crust.
3. Students will be able to present a variety of geophysical and geological evidence which may be used to prove or disprove theories of continental drift and sea-floor spreading. They will be able to suggest methods by which such theories may be tested at present or in the future.

MATERIALS REQUIRED FOR ACTIVITY

Activity 10.1
Shoe box with removable top
Graph paper
Ruler
Adhesive tape
Long, thin rods (knitting needles or pencils or drinking straws)
Glue

REFERENCES

Bascom, Willard, *Waves and Beaches*, Doubleday, Garden City, New York, 1964 (paperback).
Gross, M. Grant, *Oceanography: A View of the Earth*, Prentice-Hall, Englewood Cliffs, N.J., 1972.
Moore, Robert (Ed.), *Oceanography Readings from Scientific American*, W. H. Freeman, San Francisco, 1971.
Shepard, Francis P., *The Earth Beneath the Sea*, Atheneum, New York, 1967.

AUDIOVISUAL MATERIALS

FILMS
Deep Frontier (M-H)
Earth Beneath the Sea (M-H)
History, Layer by Layer (M-H)
Restless Sea (BT)
Waves across the Pacific (M-H)

FILMSTRIP
Oceans and their Histories (M-H)

FILM LOOPS
Coastal Processes (M-H)
Deep Ocean Sediments (M-H)
Ocean Basin Topography (M-H)

Chapter 11

OBJECTIVES

1. Students will be able to explain the importance of the oceans to environment, no matter where they may be located. They will be able to explain the interaction between the ocean and the atmosphere above it.
2. Students will have a knowledge of the motion of water on Earth's surface in a three-dimensional frame of reference. They will understand the processes which cause the motion and which affect it. They will be able to explain in general terms the effect of Earth's rotation on the movement of fluids over Earth's surface.
3. Students will be able to explain the importance of temperature and salinity on the density of seawater and the importance of density on water movement. They will demonstrate understanding of the effect of surface winds not only on the horizontal but also on the vertical movements of seawater.
4. Students will be able to explain the importance of the oceans to Earth's general climate and how the oceans serve as a three-dimensional thermostat to regulate the temperature of Earth. Students will also be able to explain the effect of deviations of Earth's heat budget on the volume of Earth's oceans and the level of the sea's surface.

MATERIALS REQUIRED FOR ACTIVITY

Activity 11.1
Pencil
Paper

REFERENCES

Gross, M. Grant, *Oceanography* (2d ed.), Merrill, Columbus, Ohio, 1971.
Moore, Robert (Ed.), *Oceanography Readings from Scientific American*, W. H. Freeman, San Francisco, 1971.

AUDIOVISUAL MATERIALS

FILMS
Challenge of the Oceans (M-H)
Marine Sedimentary Research (SW)
The Earth Beneath the Sea (M-H)

FILMSTRIPS
Geological Oceanography (EBEC)
Ocean Engineering (EBEC)
Work of the Sea (HB)
Understanding Oceanography (HB)

FILM LOOP
Ocean Currents (M-H)

Chapter 12

OBJECTIVES

1. Students will demonstrate awareness of the composition of the atmosphere, how it evolved, and the importance of the atmospheric zones to life processes.
2. Students will comprehend the possible atmospheric changes produced by man and will be able to extrapolate the effect of some of these changes on Earth's climates and on man.
3. The student will show an understanding of the layered nature of Earth's atmosphere and its importance to life on Earth.

MATERIALS REQUIRED FOR ACTIVITY

Activity 12.1
Pencil
Paper

AUDIOVISUAL MATERIALS

FILMS
Magnetosphere (M-H)
The Upper Atmosphere (M-H)

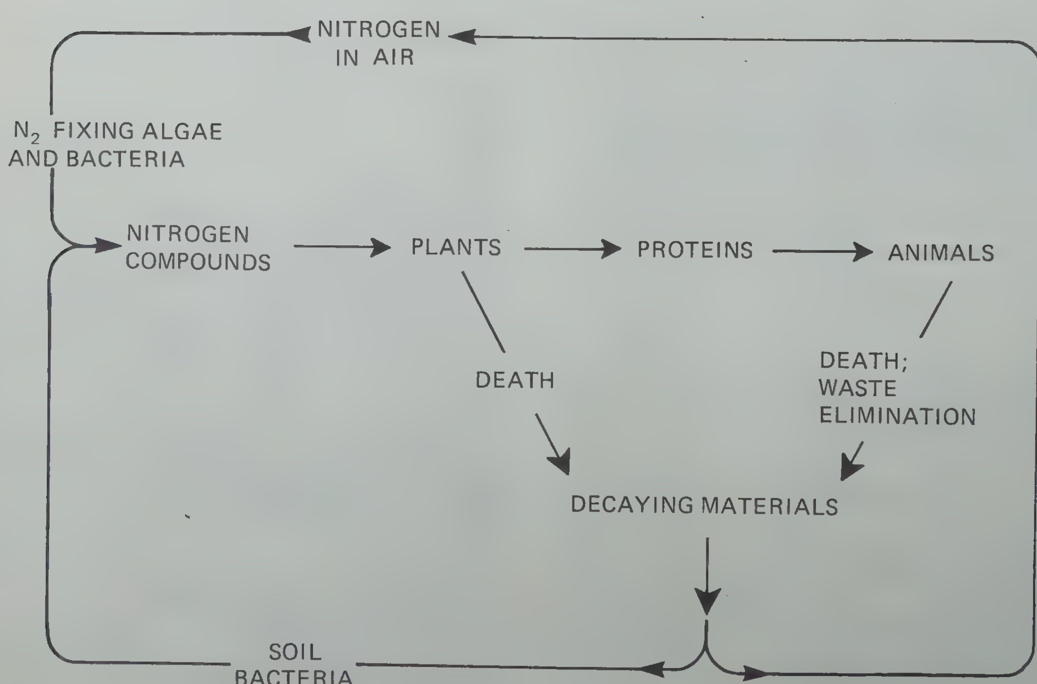
FILMSTRIP
Atmospheric Resources (M-H)

Chapter 13

OBJECTIVES

1. Students will be able to demonstrate how patterns of hot and cold and wet and dry combine to make up the patchwork of all natural environments.
2. Students will demonstrate awareness of the tight interrelationship of all the ingredients of weather.
3. Students will be able to explain Earth's thermal patterns, the distribution of air pressure and wind, and the pattern of rainfall that summarizes all of Earth's weather.

Nitrogen cycle from Activity 12.1, page 242



Comments

page 263

Introductory demonstration

A good way to introduce this chapter is to ask your students to look at Figure 13.1 and discuss the questions raised in Applying What You Have Learned (page 281) even though they have not read the chapter yet. The discussion of the various environments and the primitive shelters that evolved in them is bound to be very open-ended. (The drawings in Figure 13.1 are from "Primitive Architecture and Climate" in the December 1960 issue—unfortunately out of print—of *Scientific American.*)

The shelters are, from the top: snow igloo for winter and sod-roofed dugout for summer in the Arctic and subarctic; portable tepee and another type of tent for nomadic people living on the continental steppe (middle-latitude dryland in the continental interior); permanent adobe hut for the desert; and well-ventilated thatch-roofed hut for the tropical rain forest, often with a floor raised well above the usually wet ground. Each type of shelter evolved naturally, without the benefit of industrial technology; each is beautifully adapted to its particular environment. All are made from natural, readily available materials. No smoke-belching factories are required for their fabrication.

Stress that furnaces require the mining and burning of fossil fuels, as do fossil-fueled power plants. Nuclear power plants produce radioactive and thermal pollution. Hydroelectric plants do not require fuel, but the damming of rivers can damage the environment, especially in the long run.

Many of these shelters have natural air conditioning. For example, the thick walls of the adobe hut absorb a great deal of heat during the day (thus keeping the inside cool) and gradually release the heat at night (thus keeping the inside warm). The adobe material can be compared to the ocean; both have a moderating effect on temperature. Although it is located in a hot-and-cold environment, the adobe hut needs no air conditioning or heating, both of which contribute directly or indirectly to the pollution of the environment.

In the snow igloo, the occupants keep warm by burning an oil lamp and draping the inside of the igloo with skins and furs. The dome structure is the most windproof one we know; it also allows the least possible loss of heat through radiation from its surface, since a sphere is the solid that has the least surface area for a given volume (or, to say the same thing, the most volume for a given surface area). When mild weather comes, the igloo collapses and becomes part of natural surroundings again. No artificial, indestructible material is added to the environment.

The discussion could be closed with the question, "Why are such different environments found on Earth?" The chapter supplies the answer.

MATERIALS REQUIRED FOR ACTIVITY

Activity 13.1
Glass meatloaf pan
Medicine dropper
Colored liquid (ink or food coloring)

REFERENCES

Battan, Louis J., *The Nature of Violent Storms*, Doubleday, Garden City, New York, 1961 (paperback).

Blair, Thomas A., and Fite, Robert C., *Weather Elements* (5th ed.), Prentice-Hall, Englewood Cliffs, New Jersey, 1965.

Forrester, Frank H., *1001 Questions Answered about the Weather*, Dodd, Mead, New York, 1957.

Riehl, Herbert, *Introduction to the Atmosphere*, McGraw-Hill, New York, 1965.

Trewartha, Glenn T., *An Introduction to Climates* (3d ed.), McGraw-Hill, New York, 1968.

AUDIOVISUAL MATERIALS

FILMS
The Inconstant Air (M-H)
What Makes Clouds? (EBEC)
What Makes the Wind Blow? (EBEC)

FILMSTRIPS
Weather and Climate (M-H)
Understanding Weather and Climate (HB)

FILM LOOPS
Fronts (M-H)
Hurricanes (M-H)
Thunderstorms (M-H)

Chapter 14

OBJECTIVES

1. Students will realize that there are many different kinds of landscapes.
2. Students will know that landscapes are the result of many factors (e.g., rock structure, process, time).
3. Students will know that landscapes are con-

stantly changing and that although dramatic small-scale changes may occur rapidly, landscapes evolve very slowly by human standards of time.
4. Students will know that interaction of the factors which affect landscape development produces characteristic, large-scale surface patterns that can be recognized as physical regions.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 14.1
Earth Science textbook

Activity 14.2
Earth Science textbook
Pencil
Paper

REFERENCES

Earth Science Curriculum Project, *Investigating the Earth, Teacher's Guide, Part 2* pp. 576-601, Houghton Mifflin, Boston, 1967.
Heller, Robert L., (Ed.), *Geology and Earth Sciences Sourcebook* (2d ed.), Holt, New York, 1970.
Hunt, Charles B., *Physiography of the United States*, W. H. Freeman, San Francisco, 1967.
Shelton, John S., *Geology Illustrated*, W. H. Freeman, San Francisco, 1966.
Shimer, John A., *Field Guide to Landforms in the United States*, Macmillan, New York, 1972.

AUDIOVISUAL MATERIALS

FILM
Erosion—Leveling the Land (EBEC)

FILMSTRIP
The Earth Beneath Us (M-H)

FILM LOOP
Crustal Evolution (M-H)

SLIDES
Rahm, David A., *Rahm: Slides for Geology*, McGraw-Hill Book Company, New York, 1971.

MAPS AND AERIAL PHOTOGRAPHS
Denny, C. S., et al., *A Descriptive Catalog of Selected Aerial Photographs of Geologic Features in the United States*, Professional Paper 590, U.S. Geological Survey, Washington, D.C., 1968.
Lobeck, Armin K., *Physiographic Diagram of the United States.* The Geographical Press, a division of C. S. Hammond & Company, Maplewood, New Jersey, 1957.
Raiz, Erwin, *Landform Map of the United States*, 107 Washington Avenue, Cambridge, Massachusetts 02138, 1957.
United States Geological Survey, Washington, D.C., 20242, Fenneman's Physical Divisions of the United States, with a list of 100 topographic maps illustrating specific landforms. Available at no cost. A collection of 25 topographic maps illustrating different landforms is also available from the Survey.

Chapter 15

OBJECTIVES

1. Students will appreciate the need for conservation of our natural resources, both the renewable and the nonrenewable ones.
2. Students will realize that the United States is the largest user of raw materials, and they should be asking whether this can continue indefinitely.
3. Students will develop an awareness of the extreme danger of air pollution, water pollution, land pollution, and noise pollution. Students will also realize that they are each very important in the drive to eliminate pollution.

AUDIOVISUAL MATERIALS

FILMS
Birth of an Oil Field (SOC)
Prospecting for Petroleum (SOC)
Mining for Nickel (IN)
Riches of the Earth (CAN)
Power for People (AF)
Unseen Journeys (AF)
Treasures of the Earth (CF)
The Minerals Challenge (USMP)

FILMSTRIP
Fuel Resources (M-H)

Chapter 16

OBJECTIVES

1. Students will be able to explain the many motions of the Moon, the shape of its orbit, and why it changes phases.

2. Students will be able to demonstrate the configurations of Earth, the Moon, and the Sun required to produce lunar and solar eclipses.
3. Students will be able to explain what produces the many forms of tides on Earth.
4. Students will be able to explain why and how we know the basic characteristics of the lunar environment.
5. Students will be able to compare the gravitational pull of an object on the surface of the Moon to the pull of the same object on the surface of Earth.
6. Students will be able to state the advantages of studying astronomy from the Moon's surface.
7. Students will be able to compare the differences in the process of erosion and weathering on the Moon with those on earth.
8. Students will be able to state the basic properties of Moon rocks and their ages, as well as theories of the Moon's possible origin.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 16.1
Ruler
Pencil
Paper

Activity 16.2
Earth Science textbook
Pencil
Paper

REFERENCES

Branley, F. M., *The Moon: Earth's Natural Satellite*, T. Y. Crowell, New York, 1960.

Branley, F. M. *Exploration of the Moon*, Nelson, London, 1963.

Maisak, L., *Survival on the Moon*, Macmillan, New York, 1966.

Reizie, N. P., *The Case for Going to the Moon*, Putnam, New York, 1965.

Moore, P., and Cattermole, P., *The Craters of the Moon*, W. W. Norton, New York, 1967.

Warshofsky, Fred, *Target Moon*, Four Winds Press, New York, 1966.

AUDIOVISUAL MATERIALS

FILMS
Sun, Earth, and Moon (M-H)
Target: Moon (ACI)
Exploration of the Moon (WILEY)
Controversy over the Moon (EBEC)
To the Moon (M-H)

FILMSTRIPS
The Moon (HB)
The Moon (M-H)

FILM LOOPS
Man's First Journey to the Moon (4-loop set) (EAL)

Chapter 17

OBJECTIVES

1. Students will be able to list and explain the many unavoidable obstacles to the search for life elsewhere.
2. Students will be able to explain the probability that there may be many other worlds around other stars in our galaxy.
3. Students will be able to show, by models and examples, the relative distances between and sizes of other bodies in our solar system.
4. Students will be able to compare the suitability for human life of Mercury, Venus, Mars, and Jupiter with the suitability of Earth.
5. Students will be able to plot the positions of Mars and other planets as they change direction (loop or retrograde) against background stars.
6. Students will be able to explain why some planets change phase as seen from Earth as they orbit the Sun.
7. Students will be able to discuss the properties of comets, meteoroids, and asteroids.

Comments

pages 336-337
(3) Correct match-up for Activity 17.1

Item	Part of solar system
15-m ball	Sun
lemon	Mercury
grapefruit	Venus
softball	Earth
red apple	Mars
handful of plums	Asteroids
1.7-m ball	Jupiter
1.5-m ball	Saturn
beach ball	Uranus
beach ball	Neptune
orange	Pluto
handful of birdseed	32 satellites

pages 336-337

(4) Positions of planets and asteroids on your football field (Activity 17.2)

Body	Distance from the Sun, AU	Position on field, "yardline"
Mercury	0.39	0.97
Venus	0.72	1.8
Earth	1.0	2.5
Mars	1.52	3.8
Asteroids	2.9	7.2
Jupiter	5.2	13.0
Saturn	9.55	23.8
Uranus	19.2	48.0
Neptune	30.1	75.2
Pluto	39.5	98.7

pages 352-353

(2) The meteors are named for the constellations from which they came.

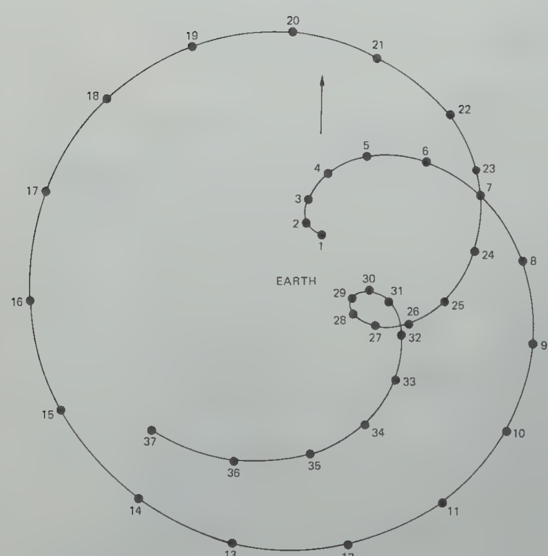
Data on meteor showers

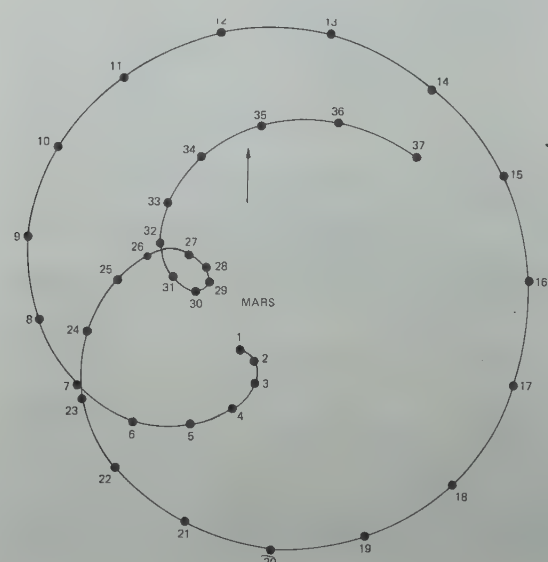
Shower	Date	Hourly sighting rate
Quadrantids	January 3	40
Lyrids	April 22	15
Aquarids	May 5	20
Aquarids	July 29	20
Perseids	August 12	50
Orionids	October 20	25
Taurids	November 5	15
Leonids	November 16	25
Geminids	December 13	50
Ursids	December 22	15

MATERIALS REQUIRED FOR ACTIVITIES

Activity 17.1
Pencil
Paper

Solution to Activity 17.3, page 346





Activity 17.2
Football field
Sheets of paper (9)
Rocks for weighting paper (9)

Activity 17.3
Graph paper, large rectangular sheet
Ruler
Pencil

Activity 17.4
Tracing paper
Pencil
Earth Science textbook

Activity 17.5
Large table OR classroom floor
Drawing compass
Flashlight
2 tennis balls

REFERENCES

Inglis, S. J., *Planets, Stars, and Galaxies*, Wiley, New York, 1967.
Moore, P., *Planets*, W. W. Norton, New York, 1962.
Page, T., and Page, L. W., *Neighbors of the Earth*, Macmillan, New York, 1965.
Page, T., and Page, L. W., *The Origin of the Solar System*, Macmillan, New York, 1966.
Ward, J. A., *Meteorites and the Origin of Planets*, McGraw-Hill, New York, 1968.

AUDIOVISUAL MATERIALS

FILMS
Other Planets—No Place Like Earth (T-L)
Exploring the Planets (ACI)
Interplanetary Space (M-H)
Science in Space (M-H)
The View from Space (M-H)

FILMSTRIPS
Introduction to the Solar System (M-H)
Mercury and Venus (M-H)
Mars (M-H)
Between the Planets (M-H)
The Giant Planets, Jupiter, Saturn, Uranus and Neptune (M-H)

FILM LOOPS
Flight to Venus (HB)
Flight to Mars (HB)

Chapter 18

OBJECTIVES

1. Students will be able to compare the dimensions of the Sun with those of other bodies in the solar system.
2. Students will understand how we can measure the distance from Earth to the Sun indirectly by applying Kepler's third law.
3. Students will be able to estimate the Sun's diameter indirectly by using similar triangles and angular diameters.
4. Students will comprehend and be able to explain how one can estimate the mass of the Sun.
5. Students will appreciate the role of the electromagnetic spectrum and spectroscopy in finding out the Sun's temperature and color.
6. Students will understand that the source of any radiation determines the type of spectrum perceived (e.g., continuous, bright-line, dark-line).
7. Students will comprehend and be able to explain the manner in which the Sun produces energy.
8. Students will be able to determine the nature of the Sun's surface features.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 18.1
Pencil
Paper
Drawing compass
Protractor
Ruler

Activity 18.2
Florist's cardboard box
Tracing paper

Activity 18.3
Pencil
Paper

Activity 18.4
Pencil
Paper

Activity 18.5
Cardboard or metal tube
Plastic diffraction grating
Black construction paper
Scissors
Glass prism (optional)
Table salt
Bunsen burner
Mercury lamp
Neon lamp
Projector
Projection screen

REFERENCES
Branley, F. M., *The Sun: Star Number One*, T. Y. Crowell, New York, 1964.
Gamow, George, *The Birth and Death of the Sun*, New American Library, New York, 1952.
Menzel, Donald H., *Our Sun*, Harvard University Press, Cambridge, 1959.
Nicholson, Thomas D., *The Sun in Action*, Natural History Press, Garden City, New York, 1964.

AUDIOVISUAL MATERIALS

FILMS
The Sun as a Star (CORF)
The Quiet Sun (M-H)
The Sun Watchers (M-H)
The Active Sun (M-H)
The Nearest Star (M-H)

FILMSTRIPS
Our Sun (M-H)
The Sun (HB)

Chapter 19

OBJECTIVES

1. Students will be able to appreciate the immensity of distances to the stars.
2. Students will be able to explain how parallax is used in measuring distances.
3. Students will realize and be able to discuss the fact that there are many different kinds of stars, differing in dimension, color, temperature, and density.
4. Students will understand and be able to explain the star-naming system.
5. Students will appreciate that the proper motion of a star causes very little change in its observed position over short periods of time.
6. Students will be able to explain the concept of the Doppler effect and its application to stellar motion.
7. Students will be able to describe double stars and explain how double stars are used to measure the mass of stars.
8. Students will be able to explain the difference between luminosity and brightness.
9. Students will be able to explain spectral classification as it relates to color and temperature.
10. Students will be able to explain the meaning of the Hertzsprung-Russell diagram.
11. Students will be able to state the properties of variable stars and the use of RR Lyrae and cepheid variables as a means of finding stellar distance.
12. Students will be able to state the properties of novas and supernovas.
13. Students will be able to state some of the properties of neutron stars, pulsars, and black holes.
14. Students will be able to appreciate that there are evolutionary changes in stars.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 19.1
A view of a clear night sky
Binoculars
Small telescope

Activity 19.2
A view of the Big Dipper, Leo the Lion, and Gemini the Twins constellations on a clear, moonless night

Activity 19.3
Pencil
Paper

Activity 19.4
Pencil
Paper

Activity 19.5
High-pitched tuning fork

Activity 19.6
Earth Science textbook
Pencil
Paper

Activity 19.7
Earth Science textbook
Paper
Pencil

REFERENCES
Chamberlain, Joseph M., and Nicholson, Thomas P., *Planets, Stars, and Space*, Creative Educational Soc., Mankato, Minn., 1964.
Chamberlain, Joseph M., *Time and the Stars*, Natural History Press, Garden City, New York, 1964.
Moore, P., *The Sky at Night*, W. W. Norton, New York, 1965.
Zim, Herbert S., and Baker, Robert H., *Stars*, Golden Press, New York, 1964.

AUDIOVISUAL MATERIALS

FILMS

The Sky Is Falling (M-H)
The Sky and the Telescope (M-H)
Fields of Space (M-H)
Eye in the Sky (M-H)

FILMSTRIPS

On the Sky (M-H)
How Far Are the Stars (M-H)
Why the Stars (M-H)
More About the Stars (M-H)
Abnormal Stars (M-H)
The Life of a Star (M-H)

Chapter 20

OBJECTIVES

1. Students will be able to state characteristics of the Milky Way and the Milky Way System.
2. Students will show an understanding of the basic principle of the rotation of the Milky Way System.
3. Students will be able to explain the nature of other galaxies.
4. Students will be able to distinguish among the three basic types of galaxies.
5. Students will be able to state some properties of the mysterious quasars. (Are they far or near?)
6. Students will be able to discuss some of the theories about the nature of the Universe.

MATERIALS REQUIRED FOR ACTIVITIES

Activity 20.1
Earth Science textbook
Paper
Pencil

Activity 20.2
Earth Science textbook
Paper
Pencil

REFERENCES

Asimov, Isaac, *The Universe: From Flat Earth to Quasar*, Walker, New York, 1966.
Hoyle, Fred, *Frontiers of Astronomy*, New American Library, New York, 1963.
King, H. C., *Exploration of the Universe*, New American Library, New York, 1964.
Lovell, Sir Bernard, *Our Present Knowledge of the Universe*, Harvard University Press, Cambridge, 1967.
Weigert, A., and Zimmerman, H. A., *Concise Encyclopaedia of Astronomy*, Elsevier, New York, 1960.

AUDIOVISUAL MATERIALS

FILMS

The Universe (M-H)
To the Edge of the Universe (M-H)

FILMSTRIPS

Eyes and Ears (Telescopes and Antennas) (M-H)
Galaxies (M-H)
Between the Stars (M-H)
The Universe (M-H)

Sources of Audiovisual Reference Materials

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New York, New York 10020

National Film Board of Canada (CAN)
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New York, New York 10019

Ohio State Univ. Motion Picture Div. (OSUMPD)
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Columbus, Ohio 43210

Popular Science Publishing Co. (POPSCI)
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New York, New York 10017

Prism Productions (PRISM)
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Shell Oil Company Films (SOC)
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Indianapolis, Indiana 46201

Southwest Film Industries (SW)
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Time-Life Films (T-L)
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Motion Picture Service
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Berkeley, California 94720

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Bureau of Audiovisual Instruction
1600 R Street
Lincoln, Nebraska 68508

Ward's Natural Science Establishment, Inc. (W)
P.O. Box 1712
Rochester, New York 14603

EARTH SCIENCE

CHALLENGES TO SCIENCE

Teacher's Edition

EARTH SCIENCE

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(Challenges to science)

SUMMARY: A science text book for the middle grades which stresses basic, general concepts of earth science, the environment, and space science.
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2. Astronomy] I. Heller, Robert Leo, 1919–
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ISBN 0-07-028045-2

preface

Wisdom is the principal thing;
Therefore get wisdom;
And with all thy getting get understanding:

Proverbs

Although one of the major objectives of this book is to help you get wisdom, the authors hope that more than anything else you will get understanding—an understanding of your environment.

With this thought foremost in mind, a sincere effort was made in writing the book to de-emphasize description and memorization, to emphasize concepts and processes, to include a large number of meaningful, interesting activities, and—last but not least—to make the book short enough and simple enough so that you will enjoy using it.

Throughout the book, not just at the end of sections or chapters, questions are asked—in some places formally, in others informally. The questions are asked to help you develop a better understanding of Earth and the universe. If you make an effort to formulate an answer to most, if not all, of these questions, and if you take an active part in performing each of the Activities in the book, you, too, will come to appreciate the ancient Chinese proverb:

I hear . . . and I forget
I see . . . and I remember
I do . . . and I understand

To leave you with the impression that there are answers to all the questions asked in this book would be misleading. One of the things that makes the study of Earth science exciting is the fact that there are still many unanswered questions—questions such as: "How was Earth formed?", "What is the energy source of volcanoes?", and "Is there life elsewhere in the universe?"

Now, are you prepared to get understanding?

The Authors

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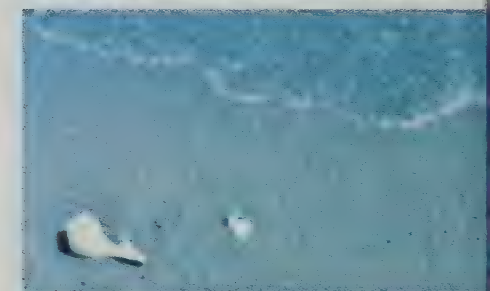
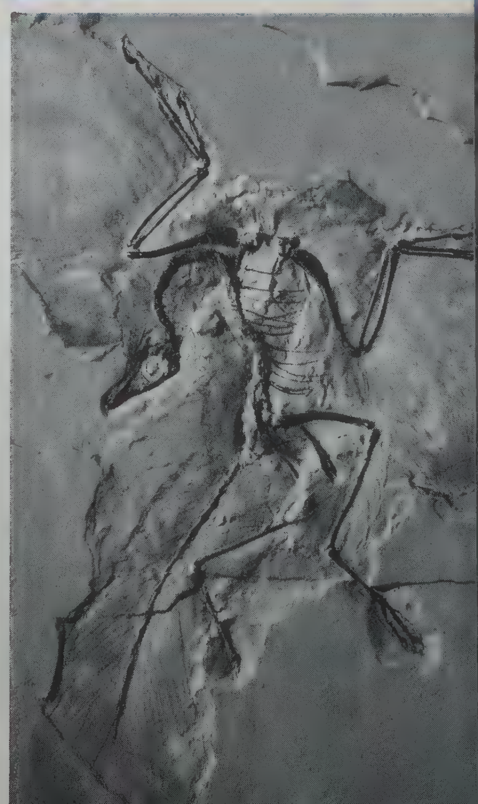
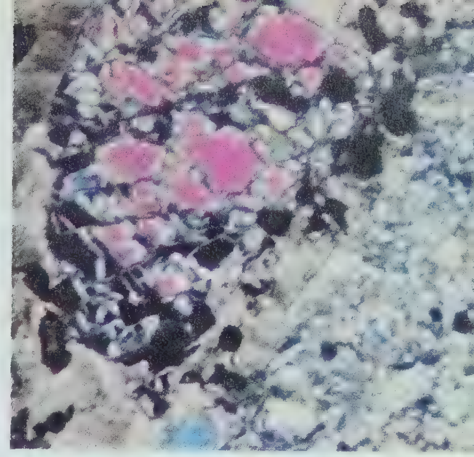
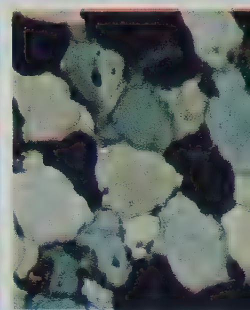
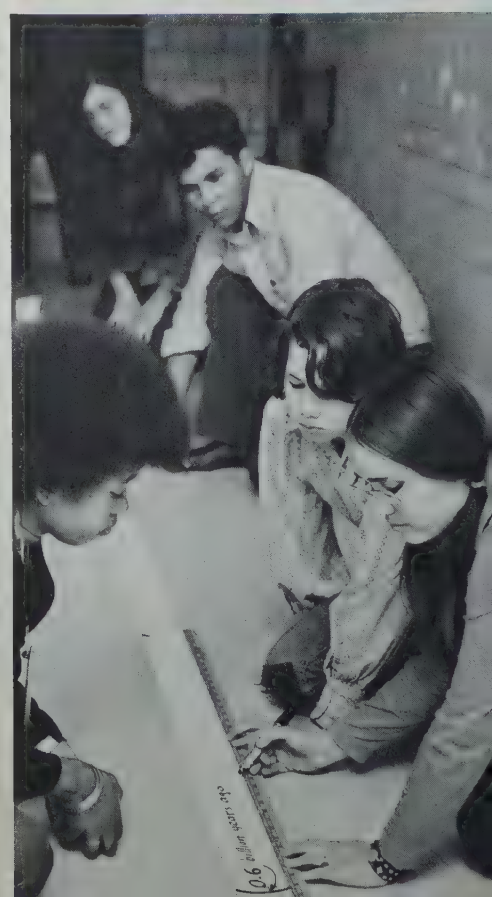










unit one

A Beautiful Planet

Imagine that some intelligent living beings from somewhere in space were sent to investigate the planets orbiting around a certain star, S. The planet they found particularly interesting was a beautiful blue and white one, the third from S. They called it S_3. The chapter you are about to read is a translation into English of their preliminary report on that planet.

Figure 1.1 The planet S_3 and its only moon differ greatly, as we could see while observing S_3 over the horizon of its moon.

Introductory Demonstration

Using an overhead projector, project a copy of a photograph of Earth taken from space by the Apollo astronauts. Tell your students that this is an unknown planet, and ask them to make observations about its nature. Write these observations on the chalkboard, then ask your students to put the observations together and see if they have described Earth. This will alert them to the things explorers must look for on alien worlds.

chapter 1

Preliminary Report on S_3

The star S is about 484 light years from us, and has nine large (1) satellites, or planets, orbiting around it. Since our time was limited we decided to investigate only S_3, the planet that seemed most interesting to us. Most of the planets have their own satellites, or moons, orbiting around them. S_3 has only one moon. S_3 and its moon are strikingly different from each other, as can be seen in Figure 1.1.

(1) See Commentary, page T7.

Orbital and rotational motions. S_3 is at a distance of about 150 million kilometers from S. It is a nearly spherical body with a diameter of about 13,000 kilometers. It has two basic motions: orbital motion around S, and rotation on its own axis. Both motions are in the same direction west to east. The axis of S_3's rotation is not perpendicular to the plane of S_3's orbit about S; it is tilted from the perpendicular by about $23\frac{1}{2}$ degrees (Figure 1.2). Why this tilt exists is not known to us, but it has strong effects on the climate of S_3. If we take the time for one rotation of S_3 on its axis to be 1, then the time for one orbit of S_3 around S is approximately 365. (2)

(2) The number 365 refers to our year, of course. The definition of a "year" is not simply the time required for one revolution of Earth around the Sun. Our calendar is related to a Sun-Earth relation involving 365 days, 5 hours, 48 minutes, and 46 seconds. Because this causes an excess of nearly 6 hours every calendar year, every fourth year we add a day to February and have a "leap year."

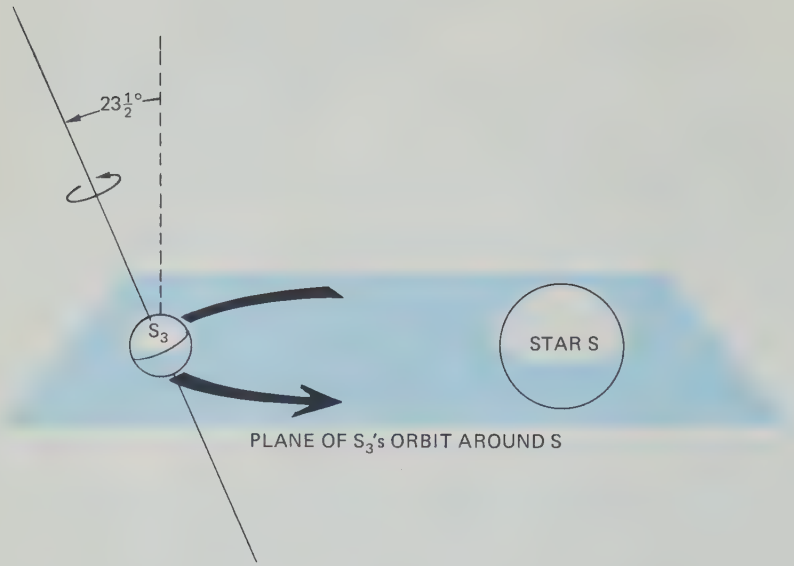


Figure 1.2 As S_3 orbits around star S, the planet rotates on its own axis. Curiously, the axis of S_3 is tilted; it is not perpendicular to the plane of its orbit. The tilt is about $23\frac{1}{2}$ degrees.

(1) **(1)** Our distinct seasons are the result of Earth's tilt of $23\frac{1}{2}°$. Figure 1.2 shows the Northern Hemisphere tilted away from the Sun, so the United States would be in winter. If S_3 (Earth) were to the right of the Sun, as it would be 6 months later, the Sun's rays would be striking the Northern Hemisphere more directly and summer would prevail.

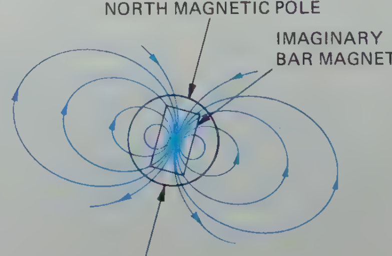
At the equator, the actual speed of rotation is about 1700 kilometers per hour. The planet moves in its orbit around Sun at about 107,000 kilometers per hour.

Magnetic field. S_3 is unusual in that it has its own magnetic field. The only other planet around S that seems to have a magnetic field is S_5. The field of S_3 is shaped somewhat like the field of a bar magnet, with the magnetic lines of force coming together at two points on S_3's surface, the magnetic poles (Figure 1.3). These poles do not correspond exactly to the poles of rotation. In fact, both magnetic poles are located many kilometers from the poles of rotation.

In addition to light and other kinds of electromagnetic radiation, S also gives off atomic particles, mostly protons and electrons. In our orbits around S_3 we noted that S_3's magnetic field is not exactly the way it is shown in Figure 1.3, but is warped by these particles. This flow of particles from S squeezes the magnetic field against S_3 on the lighted side and forces it out to a long tail on the side away from S (Figure 1.4).

The magnetic field of S_3 acts as a shield to prevent many of these particles from S and other particles from space from reaching the planet's surface. The particles are trapped in the field's inner regions, shown in color in Figure 1.4.

Figure 1.3 S_3's magnetic field is somewhat like that of a bar magnet. As with a bar magnet, the magnetic lines of force come together at two points on S_3's surface—the magnetic poles.



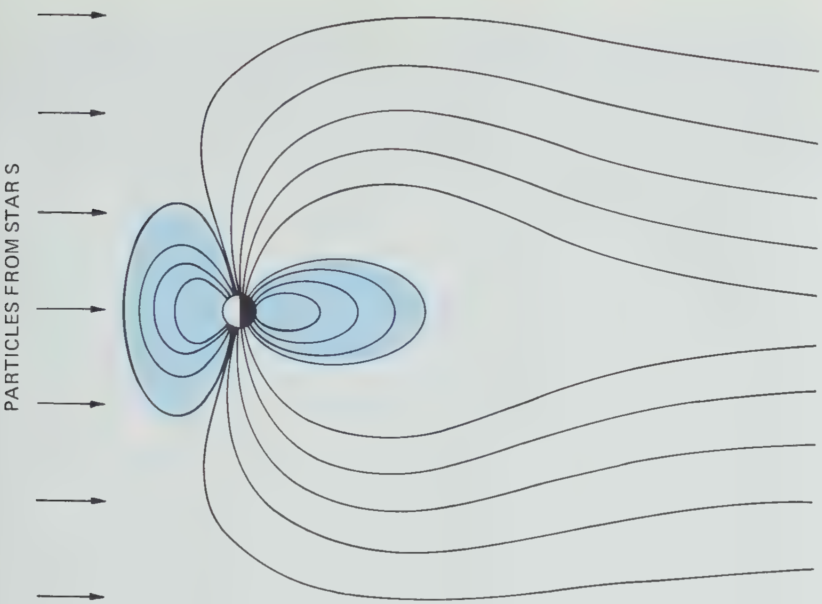
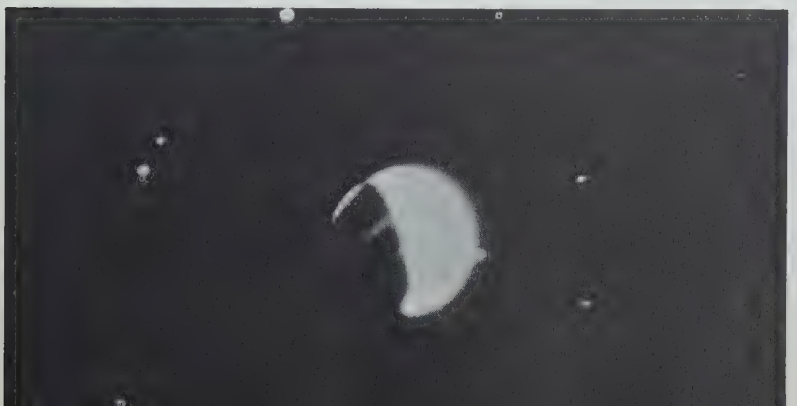


Figure 1.4 A flow of particles from S squeezes S_3's magnetic field on one side and forces it out to a tail on the other. The magnetic field shields the surface, trapping many particles (color).

Atmosphere. S_3 has an atmosphere that extends thousands of kilometers into space. However, over 98 percent of it is in the lower 35 kilometers. The gas is nearly all nitrogen (78 percent) and oxygen (21 percent). Oxygen in the form of a gas is rare in planetary systems known to us. Its presence in such large quantities is one of the most puzzling facts about S_3. The outermost part of S_3's atmosphere (above an altitude of about 2500 kilometers) is made up mostly of hydrogen, the most abundant substance in the universe. When viewed under the right conditions, this envelope of hydrogen gives off a glow that forms a beautiful halo around S_3 (Figure 1.5).

Figure 1.5 The outer part of S_3's atmosphere is mostly hydrogen. Under the right conditions, the hydrogen can be seen to glow.



Appearance from orbit. One of the most striking things about S_3 is its color. Remarkably, it is mostly blue and white. Some areas of brown and of bluish green can also be seen. There are two kinds of white substance. One kind is located largely at the south pole and in areas near the north pole, and the other kind is in the form of clouds moving about in S_3's atmosphere and often forming complex swirling patterns.

We analyzed the light from the blue areas to determine what the blue stuff was, and we also analyzed light from the white polar areas and from the white clouds. The results were so astonishing that we could not believe them. We will go into this further in our description of surface features. For the moment we shall just note that the blue stuff covers three-fourths of S_3's surface and does not vary much in height.

The brown and the bluish green areas and the white polar areas rise above the blue stuff. We shall call these areas "continents." Our beam scanners indicated that the average height of the continents is only about 800 meters above the level of the blue stuff, although some rough, elongated areas on the continents are over 8000 meters above the blue level. The highest spot we found was over 8800 meters high.

We observed some very curious patterns on the continents. An example is shown in Figure 1.6. The patterns are best developed in lower areas and can be seen in both the brown and the bluish green regions. At first we thought they were produced by some civilization but later we found this was not so.

After many orbits at altitudes of hundreds of kilometers, we began a very slow descent into the dense part (the lower 35 kilometers) of the atmosphere. At these altitudes, scattering (1) of light by the atmosphere causes S_3's horizon to appear fuzzy. As we descended, the bluish green areas appeared greener as less and less atmosphere came between us and the surface. We also noted that more of those white clouds occurred over green areas than over brown areas. The green must have some relation (2) with the clouds. Chemical scanning of the green areas indicated a complex group of compounds with the element carbon as a base. We could see that objects on surfaces of loose rock particles were responsible for the green color. Later we found these to be living organisms! The brown areas were simply regions where these life forms were few or absent.

As we came beneath the clouds we flew over all areas of S_3 and mapped it. Figure 1.7 is a result of our mapping effort. As we beam-scanned S_3, we found that the beam penetrated the blue areas! The blue stuff lies in large depressions on the

(1) Earth's atmosphere causes enough distortion of light to affect the sharpness of the image in telescopes. This is one reason astronomers have wanted telescopes on artificial satellites which orbit above most of Earth's atmosphere.

(2) The green is, of course, growing plants. The relationship with clouds is obvious.

Figure 1.6 Complex patterns like this were observed on the continents of S_3, especially in the lower areas. The patterns can be seen in both the brown and the bluish-green regions.

planet. These depressions average nearly 4000 meters deep (3) and are very rough in some parts. The roughest and highest areas of the depressions and the roughest and highest areas of the continents both have curious patterns: They are in long, irregular strings curving over the surface. This is easily seen on the map.

(3) The oceans are often said to be in "basins." However, the depressions are really very shallow in comparison to the entire size of Earth. Oceans, more accurately, are in "saucers."

Another curious fact about the continents: Between some continents there are curved chains of "islands"; each island is a small brown or green area exposed above the blue stuff. Area ALU on the map of S_3 is an example of a curved island chain. Also, note the shape of the east side of continent SA and the west side of continent AFR; they look as if they could fit together. Figure 1.8 is a more detailed map of the depression between these continents. The high elongated ridge (below the blue stuff) lying between the two continents runs nearly parallel to their coasts. Very curious indeed. There must be some reason for this, but we were unable to think of one.

The landing site we chose is marked X on Figure 1.7. We chose the site for several reasons. The site was near the blue stuff, there were some fairly large areas of blue stuff in the middle area of the continent, there were large areas of green

Figure 1.7 All of S_3's surface is represented on this map. The blue stuff, which lies in large depressions, covers most of S_3.

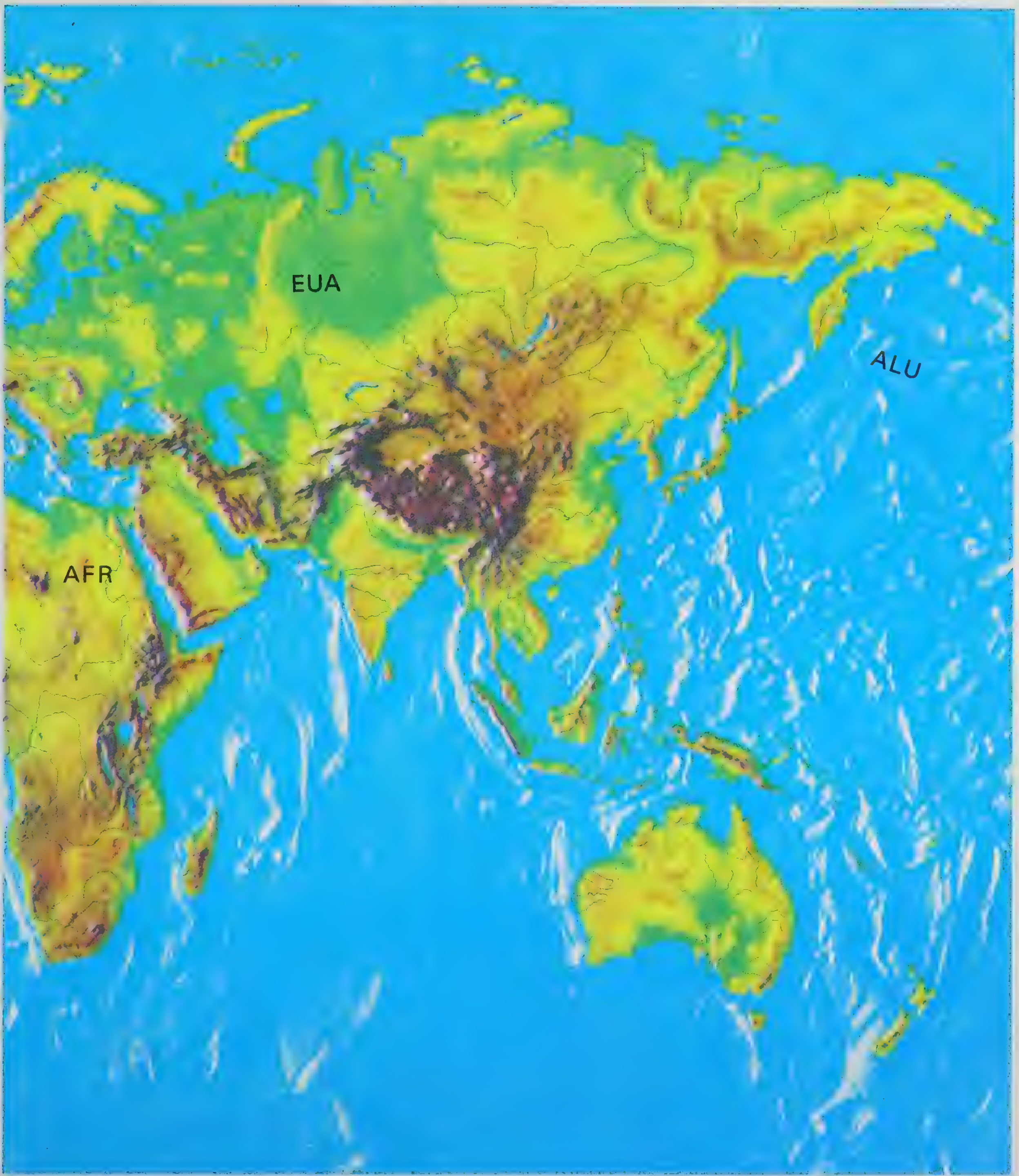


Figure 1.8 (next page) This map shows one of the depressions in more detail. The long ridge (MIDA) runs nearly parallel to the coasts.


EUA
NA
MIDA
AFR
SA

things, there were brown areas farther west, and there were both flat and rugged regions. Continent NA also has many small blue areas inland, more than most other continents, but we never did find out why.

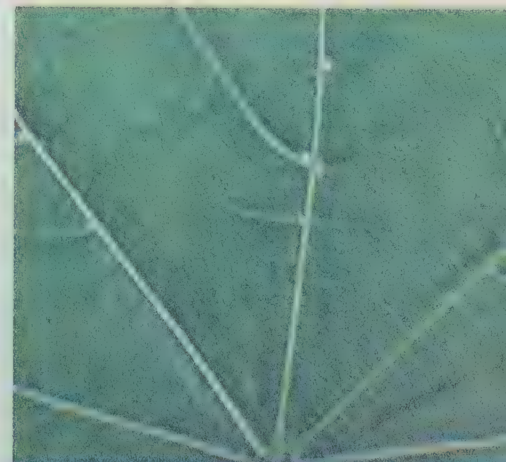
(1) The reason why NA (North America) has more lakes than most other continents is the result of glaciation. The most northern part of the United States and nearly all of Canada are largely (1) covered by loose rock debris from the last glacier, which receded less than 10,000 years ago. This debris has many water-filled depressions and the ice itself carved many depressions in the preexisting rock. A common highway map of Ontario and one of Kansas will illustrate the difference: Most of Kansas never was glaciated and has far fewer lakes. The extraterrestrial beings, not being very familiar with water, probably wouldn't have had experience with the results of continental-sized sheets of ice.

Across the surface of S_3. Upon landing we decided to go directly to the blue stuff. When we got out we found ourselves in the midst of the green things. There were countless numbers of them of all shapes and sizes. The same kind could be from a few centimeters high to about 30 meters high. These things were clearly living and growing! They are similar to food-producing organisms we have seen on a few planets around other stars. We shall call them "plants." Figure 1.9 shows some typical ones. The most dense growth was in areas open to light energy from S. The plants are very pleasing organisms to look at and are of many different shades of green. When we closely examined the green parts of the larger plants we noticed a pattern of ridges (Figure 1.10) that are very similar to the large patterns on the surface of S_3 that we had seen from orbit (Figure 1.6). We then concluded that these large patterns were gigantic plants! However, as we later discovered, we were again wrong.

We tried to communicate with many of the plants. Since they made no sounds we thought that they probably could not hear. Nor did they respond when we touched them. And, although they appeared to need light from S, they did not seem to have any image-forming organs. None of them would communicate with us, or maybe they couldn't.

Figure 1.9 (below left) The green things we had seen from above turned out to be living organisms. Places open to light from S seemed to have more of these organisms.

Figure 1.10 (below right) Closer observation reveals a pattern of ridges on green parts of larger plants.



We removed the loose stuff from around the base of some plants; this loose material is broken-down rock, some of which is chemically changed. The plants send out extensions deep into the loose material. We realized that they probably feed through these, so we covered them back up. Since we couldn't feed one aboard ship and since we didn't want to make them enemies by killing one, we brought no live samples back.

We continued toward the blue stuff, which we could see in the distance. After a short way we came to an open area where the large green organisms did not grow. The area was covered with a very short type of plant. Here we discovered a moving organism! This kind of organism is somewhat more familiar to us and we shall call it an "animal." We saw it put some parts of (1) plants into an opening in the front part of its body. It could move rapidly, and as it came near us we could see that it went along by moving extensions of its body that touched the ground. It tried to communicate with us by speaking very loudly and quickly. It seemed very excited and surprised to see us. We tried to communicate back for about an hour and used all the interstellar languages we knew. But we had to give up. Understanding this or any of the other animals we later met will have to await the arrival of language experts on future visits. Our later encounters with many different animal forms did little to further our understanding of their form of government. No one seemed to be their leader. However, they showed many intelligent patterns of behavior; for example, although some ate plants (which strangely enough didn't seem to mind) and others ate smaller animals (which seemed to mind very much), none were seen to kill except for food. Their methods of movement are very strange; they wiggle along, they run, they fly in the atmosphere, and some do another thing in the blue stuff for which we have no word or expression.

(1) A discussion about the nature of the animal might be initiated. What would the extraterrestrials have thought if they had met an angry bear instead of something like a chipmunk?

We continued toward the boundary line between the continent and the blue stuff. The atmosphere is in motion, as one would expect, since the gas is exposed to heat from Sun. This motion causes the plants to sway back and forth. As we approached the blue stuff we found that it was liquid, and that movements of the atmosphere made waves that caused it to wash against the shore. The liquid did not look so blue here; it was green, brown, or almost colorless (Figure 1.11). When we sampled it, our suspicions were confirmed. It is liquid water! This rare substance is here on S_3 in huge quantities! We must admit we wasted a great deal of time shouting and excitedly flopping about in it. Here were riches beyond com-

Figure 1.11 The blue stuff that covers so much of S_3 is liquid water. Waves in the water are made by movements in the atmosphere.

prehension. What a fortunate thing it is that S_3 exists in such a very narrow range of temperature to permit liquid water. The limited analysis we could make indicated that the water is not pure, but contains salts and other dissolved substances. Its density is therefore slightly higher than the universal standard of 1 for pure liquid water. The blue color must be due to the way light is absorbed and scattered in the water when very large quantities are observed. Many animals live in the water, and some move through it by wiggling their bodies and using winglike extensions. We did not have the equipment to study the organisms, but we brought back some external skeletons of dead ones washed up on the shore (Figure 1.12).

When we began our overland journey westward we came to one of the elongated high areas. This one was much smoother and more rounded than some others we had seen on our mapping flight. On the approach to these highlands we crossed many large and small irregularly curving strips of flowing water. This water is different from the water in the large areas; it has a density close to 1, and contains less dissolved material. When the channels of flow were mapped, it was evident that these, not plants, were forming the large patterns on the continents shown in Figure 1.6.

When we realized that there were two main kinds of liquid water, we re-examined our scanning records from orbit and made a rough computation of the amounts of frozen water, pure liquid water, and the liquid water with the dissolved salts in the big blue areas. (Our orbital scanning had indicated that the blue stuff was liquid water, the white clouds were very small droplets of liquid water, and the white polar stuff was frozen water; however, as we said, we could not believe our results.) Over 97 percent of the water of S_3 is the kind with salts, about 2 percent is frozen water, and *less than one percent* is liquid pure water! The latter amount includes all that flows, all that is in the loose ground, or is in the atmosphere. This very small percentage of nearly pure liquid water keeps all the land animals and plants alive and, we discovered later, wears away the rocks. It would not take much carelessness on the part of visitors to pollute this small amount of pure liquid water and kill many of the living organisms.

When we got near the high areas, the rocks were exposed and not covered by loose material. We were able to identify the once molten rocks, since we had seen similar ones on other planets. Some areas had broad exposures of rock types we had never seen. These did not appear to have ever been melted.

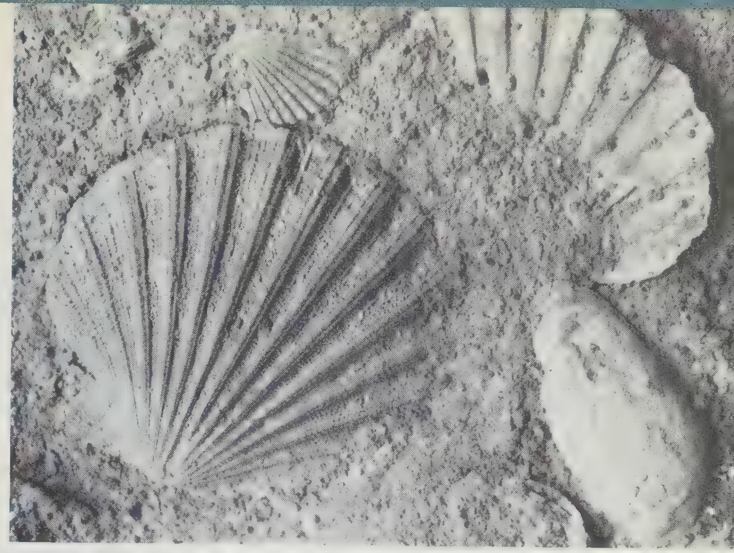


Figure 1.12 (left) Many animals live in the water. We found external skeletons of dead ones on the shore.

Figure 1.13 (right) We also found external skeletons within layered rocks high above the salty water.

They formed layers, and these layers could be followed and seemed to be fairly much the same for several kilometers. Some were lying flat and others were tilted. The layers were usually a few centimeters to a few meters thick.

After analyzing some of the rocks, we found many elements were present. S_3 seems to be a planet with two-element systems. The atmosphere is mostly nitrogen and oxygen, the water is hydrogen and oxygen, and the rocks are mostly silicon and oxygen.

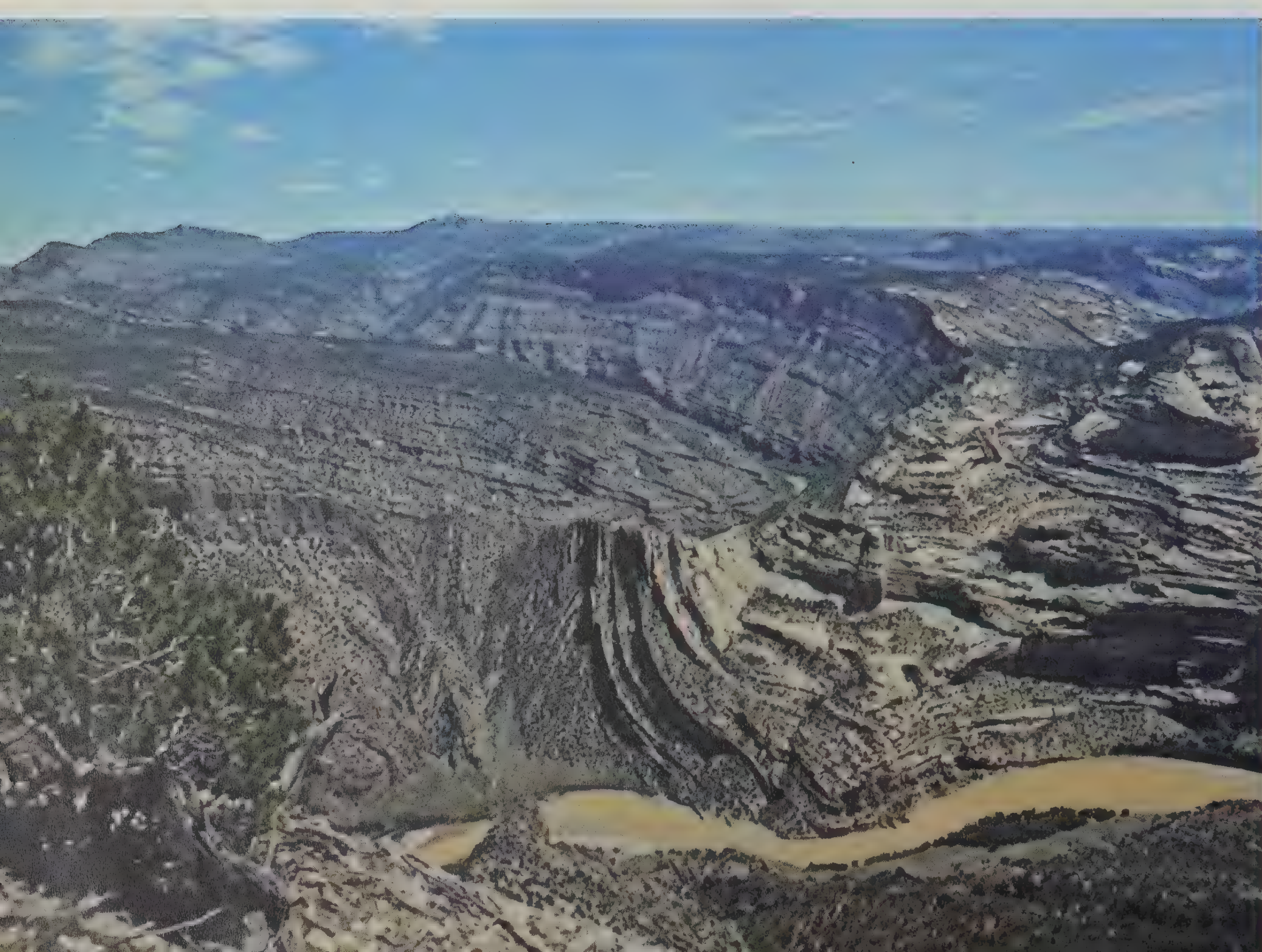
As we began to glide up toward the top of the high area to look at more of the layered rocks, an almost unimaginable thing happened. The clouds gathered over us and water in drops fell from above! Some went into the loose material in which the plants grow, but later some flowed down the surface of the slopes. This water looked brown because it was carrying fine pieces of the loose ground material. We followed the water back down and it finally went into one of the larger flow channels that had worn down through the rock. These seemed to flow toward the large areas of blue water. Obviously the surface of S_3 is being worn away! From some rough calculations based on our maps and the amount of dropping water we experienced during our stay, we computed that most of the continents on S_3 will be worn away and reduced to a level surface in only a few million years. If this is true, there are some difficult problems to solve. For example, if our calculations of the age of S and its planet system are correct, why hasn't S_3 been worn level already?

As we went back up and looked at more of the layered rock, we found another amazing thing. There were skeletons of animals enclosed within some of the layered rocks (Figure 1.13). Some of them looked very similar to the ones we saw

washed up on the shore of the big blue salty water region; yet they were found far up on the high area! This was our first clue about what made the layered rock. They may have been formed under water! How the water got so far from its basins or how the water-laid rocks got so high is a problem for the future. Along much of our route of exploration we found these traces of animal skeletons in the rocks. Sometimes we found them thousands of kilometers from the big areas of salty water and sometimes nearly 3000 meters above its level!

The layered rocks are often seen to be twisted and bent (Figure 1.14). What forces cause this are unknown, but it must have happened slowly, since most of the rock layers are not badly broken up. When we got to the western part of the continent, we made some measurements of internal motion. We put a motion meter into a hole we beam-pierced in the rock. Over a period of time the meter recorded the passage of many energy waves through the rocks. One of these was large enough for us

Figure 1.14 Layered rocks can often be seen on S_3's surface. In many areas, the layered rocks are twisted and bent.



to feel, and it is quite possible that these shock waves could be large enough to cause damage. The presence of this energy inside the planet, and the fact that layered rock that probably was formed under water is now turned on edge and may form high mountains, makes one conclusion certain: This planet has been and still is an active one. The source of this energy is another problem. We do have some data that might lead to the answer. One of our measurements was to see if there was any heat coming from S_3. Most of the surface warmth of S_3 is from S. We put heat sensors down our pierced hole at a depth of several hundred meters and obtained measurements indicating that the heat flow from within S_3 in this area is about 40 calories for each square centimeter of area during a time of one orbit around S.

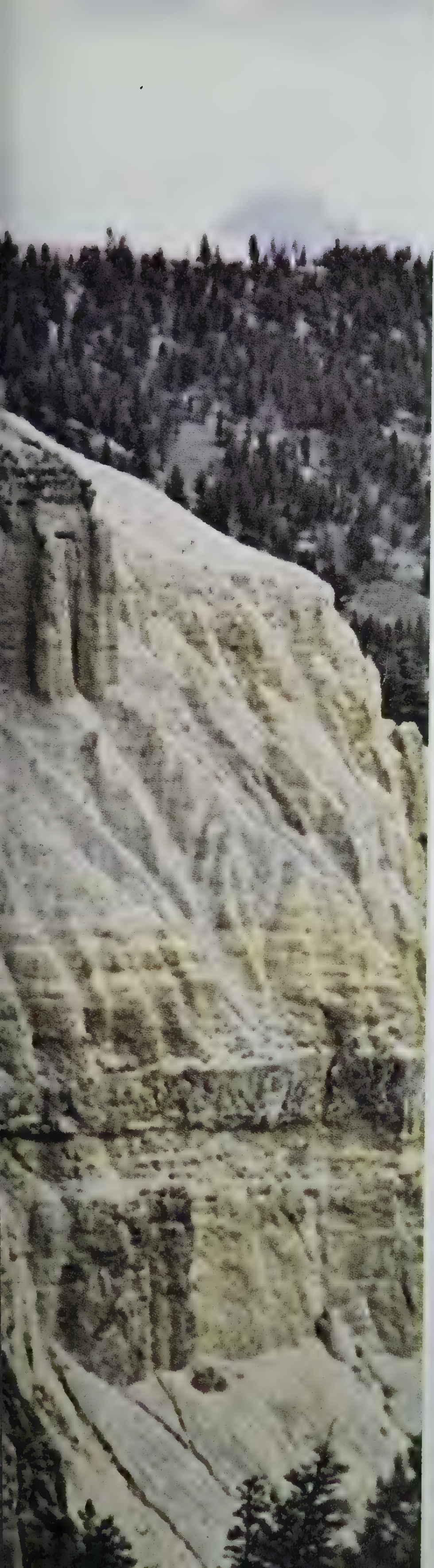
The actual temperature increase with depth, in this region of the planet, is about 30 degrees Celsius for every kilometer of depth. This internal heat probably is one of the forces that keeps S_3 an active planet. In some areas we actually observed steam and boiling water gushing out of the surface! Also, there are rocks and structures in some areas that resemble the volcanoes we have seen on other planets in the galaxy. We did not see any of S_3's volcanoes erupting, but there may be some active ones on the planet.

There is another problem about this heat. If the rate of heat increase of 30°C per kilometer of depth were to continue down to the center of S_3, the innermost region of the planet would be about 200,000°C! Since any magnetic substance that we know of loses its magnetism when heated less than one thousand degrees, how can S_3 have a magnetic field?

(1)(1) This temperature increase with depth does not continue to Earth's center. Most of the heat in the outer crust of Earth is generated within the crustal rocks themselves. This will be developed later in the text.

Summary. We have presented, in this preliminary report, some of the main problems we found that have to be solved before we can say we know much about the planet S_3. The public will be very interested (since they paid for the journey of investigation) to know of this unusual place. We tried, during the trip home, to think of a name for S_3. We concluded that only one name really describes it—Water.

To know this dynamic, changing planet will require much effort on our part. Perhaps, if future language teams decipher the communications of the living things on Water, we will find they have already studied their home. At any rate, they are lucky organisms, for they live in a beautiful place full of natural resources, with a clear atmosphere and pure water. Future visitors must be instructed to keep it that way.



unit two

The Changing Crust

Nearly 2500 years ago it was written, "Generations come and generations go, while the Earth endures forever" (Eccl. 1:4). Earth does endure, but not without change. It may seem to us, as it probably did to the author of Ecclesiastes, that Earth is always the same. We can see little change in the physical features of Earth and in the forms of life on Earth during our own lifetimes. But Earth is always changing. Some events on Earth, such as volcanic eruptions and earthquakes, are rapid. But most changes are slow. Minerals and rocks change. Mountains change. Continents change. And the rock record tells us that Earth is not just changing now; it has *always* been changing. Recently a new cause of change has become important—man. Man is changing the planet on which he lives, both for better and for worse.

Figure 2.1 What are these things made of?

Introductory Demonstration

Show the film, "The World of Minerals" (AIM).

chapter 2

Atoms, Minerals, and Rocks

Look at the picture on the left. What are these things? What are they made of? What is a rock made of? What is an apple made of? What are you made of? What is the planet Earth made of? What is *anything* made of?

Maybe you've heard people say that everything is made of *matter.* The word "matter" comes from the Latin word "mater," which means "mother." Matter, then, is the mother stuff. But so what? What's the mother stuff made of?

Man has been trying to explain matter for thousands of years. In 600 B.C., the Greek philosopher Thales said the basic stuff of the universe is water, as it is the most changeable. After all, he said, doesn't it change from cold, hard ice to a wet liquid to an invisible gas? The Greeks of that day liked to sit around and argue about things. Naturally, then, some Greeks disagreed with Thales. Some said air was the basic stuff, and others said the basic stuff was fire. About 400 B.C., Aristotle said that all matter was composed of four elements—fire, air, earth, and water, and that in various combinations, these elements made up everything in the world.

ATOMS

We now know that matter is made up of atoms. Amazingly, the Greek philosopher Democritus said this way back in 400 B.C. He said that matter was made up of invisibly small particles, and he named these particles *atomos*, the Greek word meaning "cannot be divided." He said that atoms are in constant motion, and combine with one another to form different substances. This is much like our modern atomic theory, proposed by an English schoolteacher named John Dalton in the early 1800s and modified some since then.

Atoms are too small to be seen, even with the most powerful microscopes. However, scientists have made models of atoms that seem to explain all that we know about them. According to the models, atoms are made up of many different kinds of smaller particles. Three of them are the most important: electrons, protons, and neutrons. **Electrons** are small particles with a negative electrical charge. They move rapidly in orbits around the center, or **nucleus,** of the atom. The nucleus is composed of positively charged particles called **protons** and electrically neutral particles called **neutrons.** In Figure 2.2 you see models of two very simple atoms, hydrogen and helium. The nucleus of the hydrogen atom is made up of just one proton, and in orbit around it is one electron. The helium nucleus is made up of two protons and two neutrons, with two electrons orbiting around it. The number of protons in an atom's nucleus is called the **atomic number** of that atom. Thus, the atomic number of hydrogen is 1, and the atomic number of helium is 2.

Shells. From Figure 2.2 you might get the idea that electrons orbit the nucleus the way the planets orbit the sun, or the way the moon or artificial satellites orbit the Earth. We do not think this is the case. The electrons do not travel in flat orbits. Rather, they seem to travel in three-dimensional **shells** around the nucleus. The shell does not have clear boundaries. A better concept of an atom is shown in Figure 2.3, which is a cross section of an imaginary model of a hydrogen atom. The ball in the middle is the nucleus (a proton), and the fuzzy cloud or mist around it represents the electron shell. However, for the sake of simplicity, we usually represent shells as circles. Hydrogen and helium, in this simplified representation, are shown in Figure 2.4.

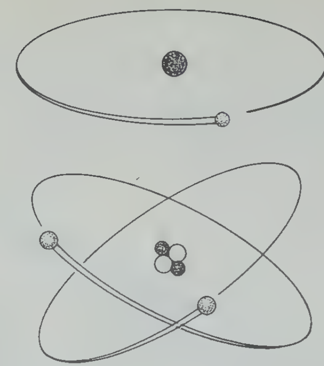


Figure 2.2 These are models of a hydrogen atom (top) and a helium atom.

Figure 2.3 In this model of the hydrogen atom, the orbiting electron is represented as a fuzzy cloud or mist.

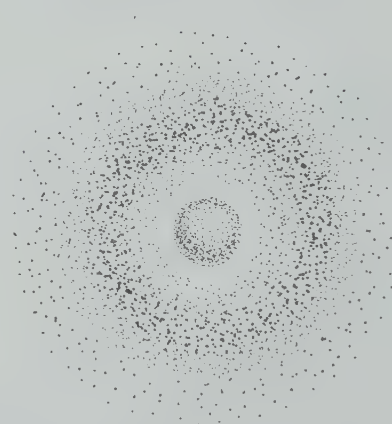
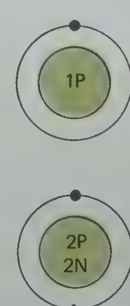


Figure 2.4 These are simplified diagrams for hydrogen (atomic number 1, top) and helium (atomic number 2, bottom).



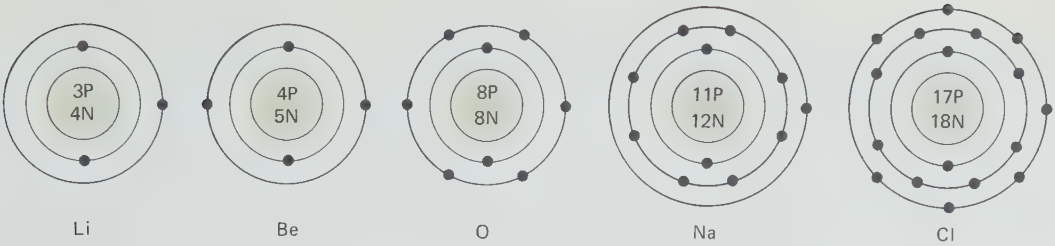


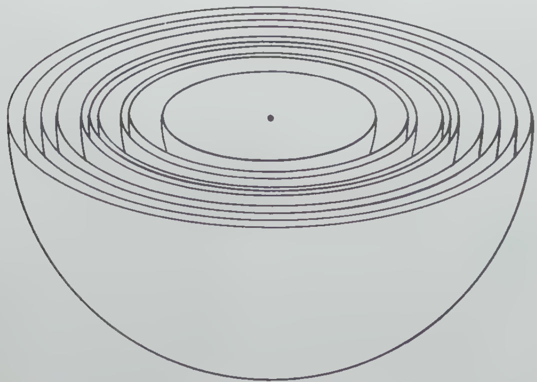
Figure 2.5 These are diagrams for lithium (atomic number 3), and for atoms with higher atomic numbers.

Let us take a look at atoms with higher atomic numbers. Figure 2.5 shows diagrams of lithium, beryllium, oxygen, sodium, and chlorine. What are the atomic numbers of these atoms?

You will notice from Figure 2.5 that the shell closest to the nucleus appears to hold a maximum of only two electrons. The next shell appears to hold a maximum of eight electrons. In an atom of sodium, which has 11 electrons, both these shells are filled, and the 11th electron has to go into a third shell. And there are shells beyond the third shell. For example, uranium (atomic number 92) has seven shells. A diagram of a nucleus and four shells is shown in Figure 2.6. Notice that each shell, except the innermost shell, has subshells as well. Well, shall we move on?

Size and mass. Have you any idea how small an atom is? Very small indeed! A chlorine atom, for example, has a radius of about $1/10{,}000{,}000{,}000$ meter. (Scientists write this as

Figure 2.6 In this diagram of an atom, the atom has been cut in half to show the nucleus in the center and the shells around it. Most shells have subshells.



0.0000000001 m or, more conveniently, 10^{-10}m. This unimaginably tiny distance is called an **angstrom,** abbreviated Å.) Suppose you took 100,000,000 atoms and laid them side by side. How long a line would this make? How many atoms, laid side by side, would be needed to make a line one inch long? (One inch is equal to 2.54 centimeters.)

(1) (1) 2.5×10^8 or 250,000,000.

Nearly all of an atom's mass (99.95 percent of it) is in its nucleus. Yet the nucleus makes up only about one one-billionth of an atom's volume. This is because the electrons are in shells far from the nucleus, making an atom very large compared to its nucleus. Figure 2.6 is not drawn to scale. If it were, the outer shell would be the length of several football fields away from the nucleus! As you can see, an atom is mostly empty space. If an atom is mostly empty space, then isn't matter also mostly empty space? Indeed it is. The chair you're sitting on is mostly empty space, this book is mostly empty space, and you are mostly empty space!

Remember, we have been describing models of what we think atoms are like. The models seem to explain all that scientists know about atoms. But as we learn more, the models will change.

Ions and crystals. If you count the number of electrons in the atoms shown in Figures 2.4 and 2.5 and compare the number of electrons to the number of protons (atomic number), you will immediately discover this relationship: An atom has as many electrons as it has protons. Since each proton carries a positive electric charge and each electron carries a negative electric charge, the equal numbers of positive and negative charges balance each other and the atom as a whole is neutral (uncharged).

However, atoms do not always like to remain neutral. What they *do* like is to have eight electrons in their outermost shells, and, to achieve this, they are sometimes willing to

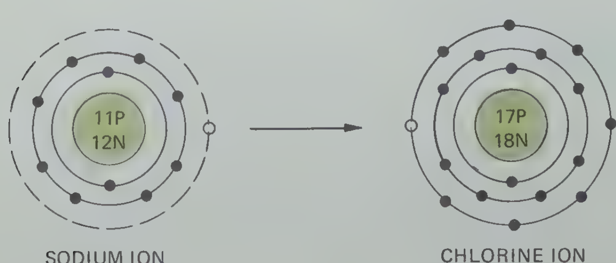
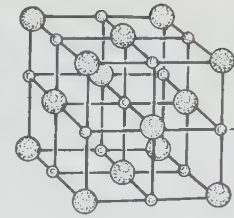


Figure 2.7 When a sodium atom gives its outer electron to a chlorine atom, both end up with outer shells of eight electrons.

sacrifice their neutrality. Look again at the sodium and chlorine atoms in Figure 2.5. The sodium has one electron in its outermost shell, and the chlorine has seven electrons in its outermost shell. Now, if the sodium atom gave its lone outer electron to the chlorine atom (Figure 2.7), both atoms will have outermost shells of eight electrons. But what has happened to the neutrality of the atoms? Since the sodium now has 11 positive charges and ten negative charges, it has a net positive charge. The chlorine atom, on the other hand, now has 10 positive charges and 11 negative charges; it therefore has a net negative charge. These atoms are now called **ions**. (Any atom that has unequal numbers of positive and negative charges is called an ion.)

As you probably know, opposite charges attract each other, and ions are no exception to this rule; sodium ions and chlorine ions attract each other. Because a sodium ion is attracted to chlorine ions, it draws chlorine ions around itself. Similarly, a chlorine ion draws sodium ions around itself (just the way a boy likes to be surrounded by girls and a girl likes to be surrounded by boys). When a collection of sodium ions and chlorine ions comes together, they arrange themselves in the way shown in Figure 2.8. Each sodium ion has six chlorine ions as its closest neighbors, and each chlorine ion has six sodium ions as its closest neighbors. Such a regular, geometric arrangement is called a **crystal structure** or **crystal lattice**, and a piece of matter made up of ions arranged in a regular way is described as **crystalline**.



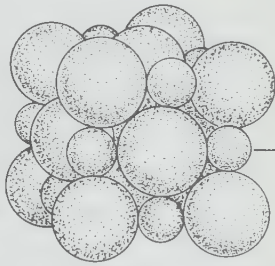


Figure 2.8 Here are two ways of representing the crystal structure formed when sodium ions and chlorine ions come together.

activity 2.1 *The shape of salt grains*

You probably know the substance that is made of sodium and chlorine ions arranged in the way we have just described. It is common table salt. Table salt occurring naturally in the earth is called *halite* by geologists. If samples of halite are available, examine their shape and the angle at which their sides meet. Carefully break a sample and examine the pieces.

Examine grains of table salt with a magnifying glass. What can you say about their shapes? Does the shape vary from grain to grain? At what angle do the sides of the grains meet?

How do you think the shape of salt grains is related to the crystal structure of salt shown in Figure 2.8?

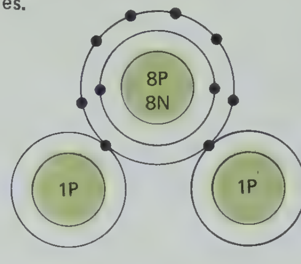
(2)(2) Students may call these grains "salt crystals." Although crystals of halite would have this shape, these are cleavage fragments which are the result of the crushing of larger halite crystals. We have not yet talked about cleavage but you may wish to refer the students to the discussion of cleavage in Appendix 6.

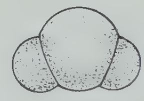
Elements and compounds. Chemists call common table salt sodium chloride; its chemical symbol is NaCl. Sodium (Na) and chlorine (Cl) are **elements**, and sodium chloride (NaCl) is a **compound**. An element is a substance made up of atoms that all have the same number of protons in their nuclei (that is, the same atomic number). There are 92 naturally (1) occurring elements on Earth, ranging from hydrogen (atomic number 1) to uranium (atomic number 92). Physicists have made about a dozen more (in atom smashers and atomic reactors) by changing the nuclei of naturally occurring elements. (What must be changed in the nucleus in order to make it a nucleus of another element?) (2)

A compound has very different properties from the elements it is made of. The element sodium, for example, is a dangerous metal that must be stored in kerosene or oil because it will explode and burn if it comes in contact with air. You certainly would never put it in your mouth. The element chlorine is a poisonous green gas; breathe enough of it and you're dead. Yet sodium and chlorine ions combine to make table salt, which you sprinkle on your food every day.

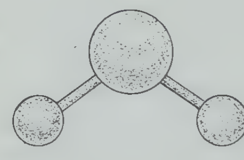
In compounds such as sodium chloride, atoms give away or accept electrons to become ions and become bonded together because of the attraction between their opposite charges. This type of bond is called an **ionic bond**. Another way in which atoms are bonded together is by sharing electrons rather than giving them away or accepting them. Hydrogen, for example, will share the one electron it has, but it won't give it away outright. Oxygen needs two more electrons to add to the six in its outermost shell. In Figure 2.9, two hydrogen atoms share their electrons with one oxygen atom. What is the resulting compound? This type of bond is called a **covalent bond**. (3)

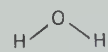
(1) This is not strictly true. Neither promethium nor technetium has yet been found in the natural state on Earth; astatine exists, but only in minute quantities.





(2) The number of protons.





H_2O

Figure 2.9 Five ways to represent the same thing: the compound formed when two hydrogen atoms share their electrons with an oxygen atom.

(3) Water.

CHECK YOUR FACTS (4)

1. Describe a model of an atom.
2. Define an element.
3. How does an ion differ from an atom?

(4) ANSWERS / Check Your Facts

1. A small, solid nucleus surrounded at a great distance by a cloud of electrons.
2. A substance made up of atoms that all have the same number of protons in their nuclei.
3. An ion is an atom with unequal numbers of positive and negative charges.

MINERALS

In the Black Hills of South Dakota, there are some crystals of spodumene (a compound made of ions of lithium, aluminum, silicon, and oxygen) that measure over 12 meters long! In

Maine, there are crystals of beryl (a compound made of ions of beryllium, aluminum, silicon, and oxygen) that measure more than five meters by one meter. A lot of the right ions had to get together to form such large crystals! Certainly not all minerals come in such large crystals. One variety of beryl is the beautiful green gem called emerald. You'll never find an emerald that measures five meters by one meter! If you did, you'd certainly be rich.

Spodumene and beryl are examples of substances called **minerals**. A mineral is a natural, inorganic, crystalline material. Both ionic and covalent bonding are common in minerals.

Why do we study minerals? Because minerals are what rocks are made of. Rocks, in turn, make up Earth's solid layers. The outer layer, the one on which we live (and which lies under the oceans also) is called the **crust**.

Elements of the crust. Although there are 92 naturally occurring elements, most of the minerals in Earth's crust are made up of only nine of them. These nine elements are listed in Table 2.1. Together they make up over 99 percent of the weight of the crust. (And they also make up over 99 percent of the volume of the crust.)

And oxygen, which makes up 47 percent of the crust by weight, makes up 94 percent of its volume! This is because the oxygen ion is large compared to the other ions. So if you pick up a rock, about half its weight and most of its volume is oxygen. As you walk on the solid ground, you are really walk-

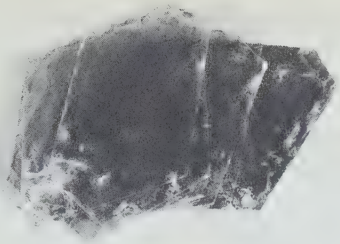
(5) For sizes of ions, see page 40.

Table 2.1 Composition of Earth's crust

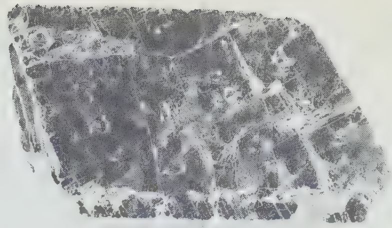
Element	Symbol	Percentage by weight
oxygen	O	46.6
silicon	Si	27.7
aluminum	Al	8.1
iron	Fe	5.0
calcium	Ca	3.6
sodium	Na	2.8
potassium	K	2.6
magnesium	Mg	2.1
titanium	Ti	0.4
all other elements		1.1
Total		100.0

Table 2.2 Common rock-forming minerals

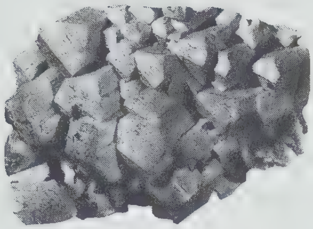
Name	Elements present	Hardness	Common color	Cleavage
muscovite mica	H, K, Al, Si, O	$2-2\frac{1}{2}$	clear	1 perfect cleavage (flakes)
biotite mica	H, K, Mg, Fe, Al, Si, O	$2-2\frac{1}{2}$	brown, black	1 perfect cleavage (flakes)
orthoclase feldspar	K, Al, Si, O	6	pink	2 cleavages at 90°
plagioclase feldspars	Ca, Na, Al, Si, O	6	white, grey	2 cleavages at 90°
amphiboles	Ca, Na, Mg, Fe, Al, Si, O	5–6	black	2 cleavages at 120°, 60°
pyroxenes	Ca, Mg, Fe, Al, Si, O	5–6	green, black	2 cleavages at 90°
olivines	Mg, Fe, Si, O	$6\frac{1}{2}-7$	green	no cleavage, glassy
quartz	Si, O	7	white or any color	no cleavage, glassy
clays	H, Al, Si, O (and some Ca, Mg, Fe, Al, Na, K)	$1-2\frac{1}{2}$	grey or brown (white if pure)	massive (very small flakes); earthy feel and smell
calcite	Ca, C, O	3	white	3 cleavages at 120°, 60°; fizzes in acid



MUSCOVITE MICA

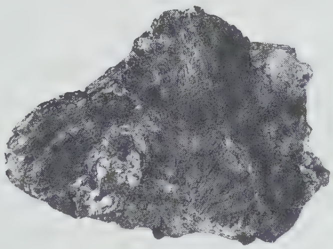


BIOTITE MICA

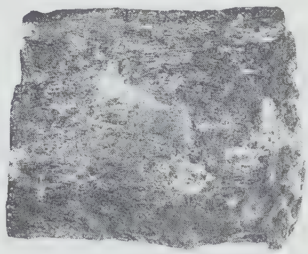


ORTHOCLASE FELDSPAR

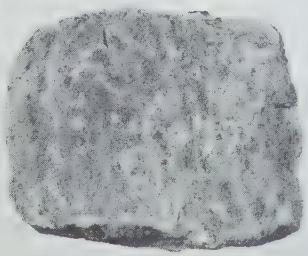
PLAGIOCLASE FELDSPAR



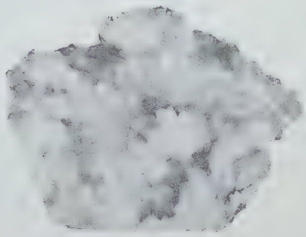
AMPHIBOLE



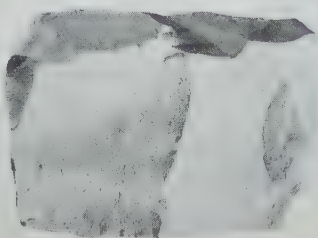
PYROXENE



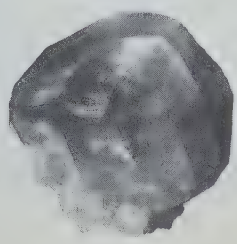
OLIVINE



QUARTZ



CLAY (KAOLINITE)



CALCITE

ing on an oxygen mattress! Oxygen also makes up about 57 percent of the weight of water and 21 percent of the weight of air. Important stuff, oxygen.

More than 2000 different minerals have been described. Most are rare. Luckily, only about ten of them make up about 99 percent of Earth's crust. And most of these are basically compounds of two particular elements, with other elements present in smaller amounts. What do you think these two elements are? And what are the other elements that are present in smaller amounts? See if you can answer these questions before reading further.

(1)(1) Oxygen and silicon.

(2)(2) Al, Fe, Ca, Na, K, Mg, Ti.

Rock formers. The ten common minerals mentioned in the last paragraph are shown in Table 2.2. They are called the "rock formers" because together they make up most rocks. Figure 2.10 shows four of these rock formers in a piece of granite, a very common rock. Many minerals other than those in Table 2.2 are present in rocks too, but they do not make up much of the weight or volume.

The general composition given for the minerals in Table 2.2 shows only what elements each mineral is made of. It does *not* give the chemical formulas of the minerals. Quartz, for example, contains twice as many oxygen atoms as silicon atoms; its chemical formula is therefore SiO_2. And the chemical formula of calcite is $CaCO_3$.

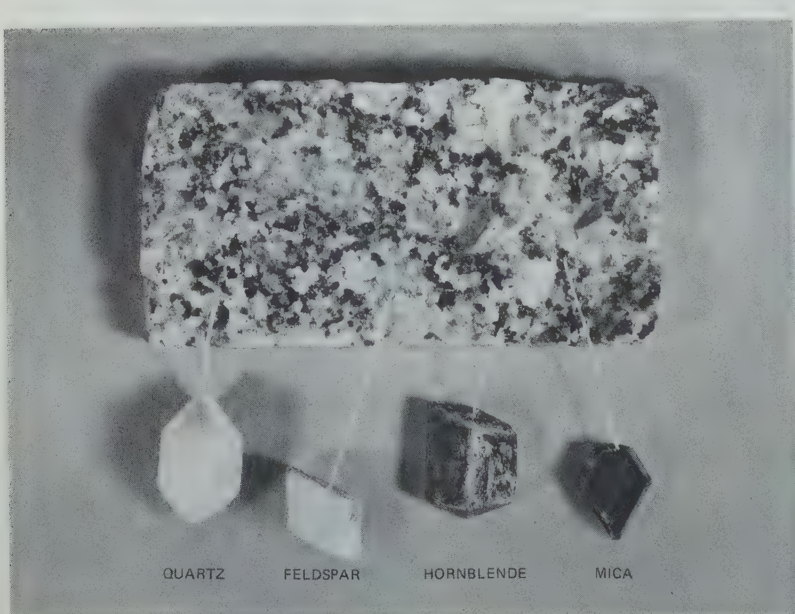


Figure 2.10 A piece of granite is shown with four of the minerals it is made of. (Hornblende is a kind of amphibole.) It is usually easy to see the different minerals in granite.

Some of the minerals in Table 2.2 have varying compositions. For example, one kind of plagioclase contains sodium but no calcium, and another kind of plagioclase contains calcium but no sodium. Most plagioclases fall in between these two extremes; they contain both sodium and calcium in varying proportions. *All* plagioclases contain aluminum, silicon, and oxygen. Similarly, all olivines contain silicon and oxygen, but they contain varying proportions of magnesium and iron. All pyroxenes contain silicon and oxygen but varying proportions of calcium, magnesium, iron, aluminum, and sodium.

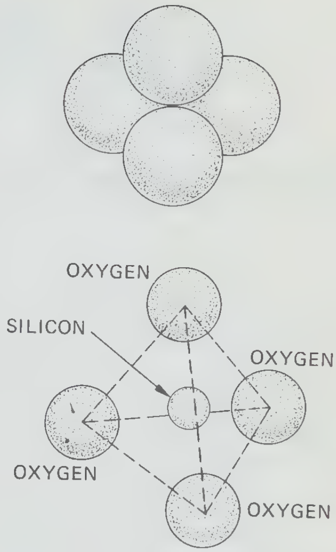


Figure 2.11 In a silicon-oxygen tetrahedron, four oxygen ions surround a silicon ion, as shown in the exploded view at bottom.

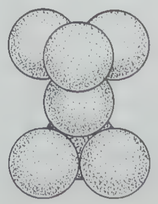
Silicates. Notice that nine of the common rock-forming minerals contain both silicon and oxygen. Such minerals are called **silicates**.

Oxygen ions have negative charges and silicon ions are positively charged. They are therefore attracted to each other. Oxygen ions are large (1.3 Å radius) and silicon ions are small (0.40 Å radius). Together they assume a four-cornered shape called a **tetrahedron**, with a silicon ion in the "hole" between the four oxygens, as shown in the exploded view in Figure 2.11. (Imagine three basketballs touching each other. Couldn't we drop a tennis ball in the hollow between them? And wouldn't another basketball fit on top?) The formula of the (3) tetrahedron is therefore SiO_4, and because of the four oxygens it has a negative charge. It acts like a negatively charged ion and combines with many kinds of positively charged ions.

(3) You might wish to actually use the three basketballs and the tennis ball. It should make the tetrahedron more interesting to some students.

One way to describe the crystal structure of the silicate minerals is to say that the silicon–oxygen tetrahedrons are the "building blocks" of the minerals. These building blocks are held together by a "glue" of positively charged ions. (Can you guess what these positive ions are?) Together the blocks and the glue make up the minerals, somewhat the way bricks and mortar make up a wall. If the glue makes a strong bond, the mineral is hard; if it makes a weak bond, the mineral is soft. And if the glue is arranged in certain layers, the mineral breaks most easily along those layers. This property of breaking along certain planes is called **cleavage**. The salt grains you examined in Activity 2.1, for example, have three cleavages at 90 degrees.

Figure 2.12 Here are two silicon-oxygen tetrahedrons sharing one oxygen.



In most silicate minerals, the silicon–oxygen tetrahedrons do not occur singly. Rather, they share oxygen atoms between them. Figure 2.12 shows two tetrahedrons sharing one oxygen atom. Such an arrangement is stronger than two

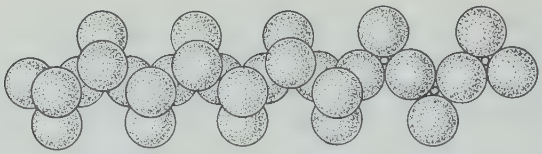


Figure 2.13 In this chain of tetrahedrons, some of the oxygens have been removed to show the silicons in the middle of the tetrahedrons.

individual tetrahedrons joined by the "glue" of positive ions. The greater the amount of oxygen sharing, the stronger the mineral. The chain of tetrahedrons shown in Figure 2.13 is found in pyroxene. The chains are held together by positive ions of calcium, magnesium, and iron. If you look at any particular tetrahedron in the chain, you will see that two of its oxygens are shared with adjacent tetrahedrons.

In mica, each tetrahedron shares three oxygen atoms with its neighbors. The tetrahedrons are arranged in flat layers, as shown in Figure 2.14. The layers are held together by positive ions. Because the silicon–oxygen bonds are much stronger than the bonds between the layers, mica can be easily broken apart into thin flakes. Geologists describe it as having perfect cleavage.

In quartz, *all* oxygen atoms are shared, making a three-dimensional network of silicon–oxygen bonds. These bonds are strong and extend in all directions. That is why quartz is so hard and has no cleavage—that is, there are no planes along which it tends to break. It breaks irregularly, in all directions. The fine grains of glassy material in most sand (often it makes up most of the sand) are grains of quartz. Although the grains may at first look like the grains of NaCl you examined in Activity 2.1, close examination will reveal many different shapes and no flat, shiny cleavage faces. (1)

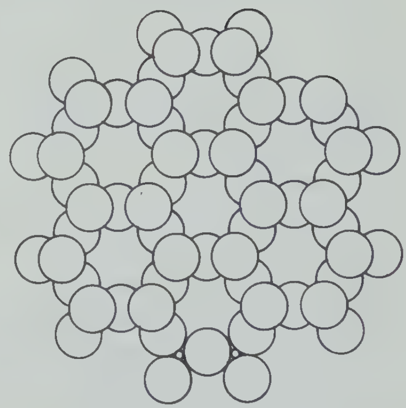


Figure 2.14 Two oxygens have been removed from this layer of tetrahedrons to show the silicons.

(1) In the feldspars, all the oxygen atoms are shared, as in quartz. However, the presence of other ions in the feldspars results in some weaker bonds and, therefore, in cleavage and a lesser hardness than in quartz.

activity 2.2 Joining tetrahedrons

A tetrahedron is made of four identical faces. Each face is an equilateral triangle (a triangle whose sides are all equal or, to say the same thing, a triangle whose angles are all 60 degrees). You can make a tetrahedron by cutting out patterns such as those shown in Figure 2.15 out of cardboard or stiff paper and

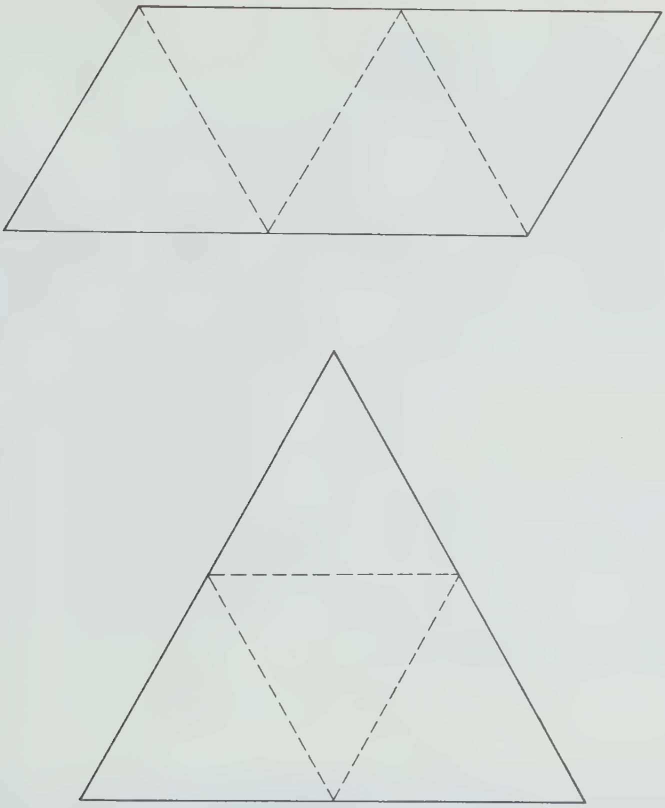


Figure 2.15 These are patterns for making tetrahedrons.

folding along the dotted lines. (Make all the folds in the same direction.) Join the edges with tape, and you have a tetrahedron. For this activity, make at least two tetrahedrons of the same size.

Imagine that each apex (the point where three faces meet) is an oxygen atom. (The silicon atom, being in the middle of the tetrahedron, can't be seen in this model.) Bring two tetrahedrons together so that just one apex of one tetrahedron touches just one apex of the other tetrahedron. This represents the sharing of one oxygen atom by two tetrahedrons.

There are many other groups of minerals in addition to the silicates. The *oxides* are made up of various kinds of positive ions joined to negative oxygen ions. The *sulfides* are made up of positive ions and negative sulfur ions. The *sulfates* are made up of positive ions and negative SO_4^{--}(sulfate) building blocks. And the *carbonates* are made up of positive ions and negative CO_3^{--}(carbonate) building blocks. Ions of many (1) valuable elements, such as silver, copper, and lead, fit more easily into the crystal structure of some of these mineral groups than into the crystal structure of silicates. This is why these other mineral groups include most of the valuable ores that man uses in his industries.

(1) Examples: (*a*) Oxides: hematite—Fe_2O_3, limonite—$Fe_2O_3 \cdot H_2O$, bauxite—$Al_2O_3 \cdot H_2O$ (*b*) Sulfides: pyrite—FeS_2, galena—PbS, chalcopyrite—$CuFeS_2$, sphalerite—ZnS (*c*) Sulfates: gypsum—$CaSO_4 \cdot H_2O$, barite—$BaSO_4 \cdot H_2O$ (*d*) Carbonates: siderite—$FeCO_3$, calcite—$CaCO_3$.

(2) **ANSWERS** / Check Your Facts

1. Oxygen (approximately 47% of crust by weight; 94% of crustal volume).
2. Silicon and oxygen, in minerals known as "silicates."
3. Chains, networks, and layers of tetrahedrons.

CHECK YOUR FACTS (2)

1. What is the most abundant element in Earth's crust?

2. What two elements are present in nine of the "rock formers"?

3. What are some ways in which oxygen and silicon are arranged in silicate minerals?

ROCKS

What are rocks? Objects to throw? The stuff that makes mountains? The hard stuff that is under the soil?

I wish I were a little rock
A-sitting on a hill
A-doing nothing all day long,
But just a-sitting still;
I wouldn't eat, I wouldn't sleep,
I wouldn't even wash—
I'd sit and sit a thousand years
And rest myself, b'gosh.

Frederick Palmer Latimer
The Weary Wisher

You may recall from elementary school that there are three main classes of rocks: **igneous, sedimentary,** and **metamorphic**. Igneous rocks crystallize from molten material called **magma** that is formed deep under Earth's surface.

Occasionally magma escapes to the surface through volcanos or through cracks; it is then called **lava**. The red hot stuff shown on the cover of this book is lava. The word igneous comes from the Latin *ignis,* or fire. Sedimentary rocks are formed from pieces (sediment) of other rocks, cemented together, or from materials such as sodium chloride that has come out of solution in water and settled to the bottom. The word comes from the Latin *sedimentum,* which means a settling, as out of water. Sedimentary rocks form as layers or **strata** (singular: **stratum**). Metamorphic rocks result when other rocks—either igneous, sedimentary, or other metamorphic rocks—are changed by undergoing different temperatures, pressures, or chemical environments. *Meta* means change and *morphe* means form.

Sedimentary rocks are the most common kind on Earth's surface, covering about $\frac{3}{4}$ of Earth's land area (Figure 2.16). However, they make up only a thin layer, a skin. Igneous and metamorphic rocks are peeking through the sedimentary layers in many places, such as the Black Hills in South Dakota and Wyoming, the Ozarks in Missouri and Arkansas, and many mountain ranges. This shows us that igneous and metamorphic rocks similar to those exposed over the $\frac{1}{4}$ of Earth's

(3) The students may guess correctly that Figure 2.16 is a view of the Grand Canyon. Ask them how they knew.

Figure 2.16 The layers in these sedimentary rocks are easily seen. **(3)**

land area are also present beneath the sedimentary cover. Igneous rocks probably make up about 95 percent of Earth's crust, which is up to 60 kilometers thick.

If a visitor from space landed on Earth, what are his chances of finding sedimentary rocks?

Rock cycle. The three kinds of rocks are related to each other as shown by the **rock cycle** (Figure 2.17). When we are talking about rocks, we are, of course, also talking about minerals, since minerals are what rocks are made of. Each mineral forms under certain temperatures and pressures and commonly in the presence of certain solutions.

As long as a mineral remains in the environment in which it formed, or where the conditions are about the same, it will be stable (that is, it will remain as it is). But if the conditions change, the mineral becomes unstable and it will alter (change) to some mineral that is stable under those conditions. For example, orthoclase may crystallize deep underground from magma at a temperature of about 1000°C and a pressure dozens of times greater than that at the surface of Earth (atmospheric pressure). If it is moved to the surface of the Earth, the temperature will be about 20°C and the pressure will be only one **atmosphere**. Also, air and water will be present at the surface. Under this completely different set of conditions,

Pressure is a quantity that represents the force being applied to a unit area of a given surface. Imagine a vertical column of air resting on one square meter of Earth's surface and extending to the top of the atmosphere. This column weighs about 100,000 newtons—that is, it pushes down on the square meter of surface with a force of 100,000 newtons. (One newton is equal to about 0.22 pound. The newton is a unit of force or weight in the metric system. The pound is a unit of force or weight in the British system.) This pressure, 10^5 N/m^2, is called *standard atmospheric pressure* or, briefly, *one atmosphere*. How many newtons per square meter is a pressure of 15 atmospheres? Of ½ atmosphere? In British units, one atmosphere is about 14.7 pounds per square inch.

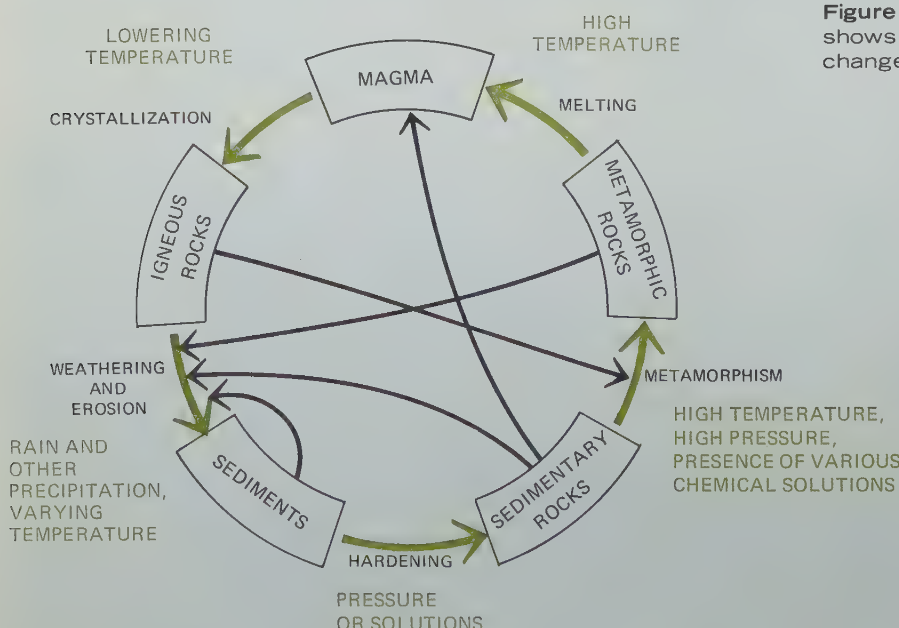


Figure 2.17 The rock cycle shows how rocks and minerals change.

the orthoclase will change to clay, a mineral that is stable at the surface conditions. However, this change is generally so slow that it is difficult to see it happening.

We can summarize the rock cycle in a few words. Minerals are stable only in the environment in which they are formed. Since rocks are made of minerals, rocks, too, are stable only in the environment in which they are formed. And because most rocks are subjected at one time or another to a change of environment, most rocks eventually change.

To tell the three classes of rocks apart, geologists describe their **compositions** and **textures**. The composition of a rock can be stated as a chemical composition or a mineralogical composition. To determine the chemical composition involves detailed laboratory study. The mineral composition is easier to determine. You can sometimes tell what minerals are in a specimen of rock just by looking at it. Or you can use a hand lens (magnifying glass) or, even better, a microscope. The texture of a rock is determined by the shape, size, and arrangement of the minerals it is made up of.

Geologists who study igneous and metamorphic rocks have the nickname "hard-rockers." Geologists who study sediments and sedimentary rocks are "soft-rockers." The soft-rockers are quick to point out that sedimentary rocks, while softer, can be the hardest (most difficult) rocks to study. This is because sedimentary rocks can contain pieces of any kind of mineral and any kind of rock. So to understand sedimentary rocks, they must also know quite a bit about igneous and metamorphic rocks and minerals. And, believe it or not, there are some geologists who might be called "no-rockers." These geologists are usually highly trained in physics, chemistry, and mathematics. They theorize and they make models—sometimes with real substances, sometimes with the help of computers, and sometimes just in their heads.

Principle of uniformitarianism. The main job of a geologist is to figure out the history of Earth. Historians study the history of man since man first recorded events; for example, there are Civil War historians and there are European historians. Geologists are historians too—Earth historians. Different geologists specialize in the history of different parts of Earth and in rocks of different ages. To study the history of Earth, geologists must study all the surviving bits of evidence, all the clues to the past. The main evidence is in the rocks themselves. But if geologists weren't around when the rocks were formed, how can they tell how they formed?

In the late 1700s, James Hutton (1726–1797), a Scotsman, spent years observing nature at work. He realized that old sedimentary rocks were probably formed by the same processes that were at work in nature all around him. He realized that just as sand on a beach today is moved by waves and currents, so sand on ancient beaches was probably moved before it was hardened into the sandstone we see today. He studied old sedimentary rocks and compared them with modern sediments and the processes now at work on the sediments. He was thus able to suggest how the old rocks formed—they were formed by the same processes that are now turning sediments into sedimentary rocks. He said that since young lava flows look like old ones, they were probably all formed by the same types of processes. Hutton also surmised that the granites of Scotland had formed from hot molten rock that had come from within Earth. (1)

Finally, in 1788, after more than 30 years of observing geological processes, Hutton stated that there was a uniformity in nature. He said that geological processes at work today had also been at work in the past. This is now known as the **principle of uniformitarianism.** In other words, "the present is the key to the past." The principle does not imply that things are happening at the same *rate* (speed) today as in the past; it just says that the same *processes* are at work today as in the past. (2)

Hutton's views were in direct opposition to the prevailing beliefs of the day. Most people thought that rocks and other Earth features were the results of major catastrophes, such as earthquakes and floods. Mountains, for example, were believed to have been pushed up in sudden, violent happenings. This principle is called **catastrophism**. Another objection to uniformitarianism was that (as Hutton himself pointed out) it required a very long time for the formation of rocks and other features, far longer than what was then believed to be the age of Earth.

One of Hutton's main opponents was Abraham Gottlob Werner (1744–1817), a famous teacher in Germany. Werner was a good mineralogist and wrote very detailed and useful descriptions of rocks and minerals, but when it came to theory he was often wrong. Although there was strong evidence to the contrary, he insisted that volcanic rocks resulted from the melting of sediments when coal beds beneath them caught fire. He also taught that the rocks we now call igneous and metamorphic rocks had formed in the water of an ocean that (3)

(1) Hutton was an interesting man. Although he earned his M.D. degree, he never practiced medicine, and later he became the founder of geology as a science. Before his death he was writing a book that postulated evolution by natural selection. Had he lived to finish this work, he would have been 60 years ahead of Darwin. As things turned out, however, the manuscript was not examined until 1947, 150 years after Darwin published his work.

(2) Emphasize that *rate* is not involved in the principle of uniformitarianism. The principle is *qualitative*, not quantitative. Even many geologists become confused on this point.

(3) Werner was a dynamic teacher, and his students loved him. As the controversies raged, his students stuck by him. But after he died, many acknowledged that Werner had been wrong.

covered the entire Earth early in its history. Thus Werner and his followers were called Neptunists, after the Roman god of the sea, and Hutton and his followers were called Plutonists, after the god of the lower world. Eventually Hutton's views were accepted by nearly everyone, but not during his lifetime. (4)

Hutton wasn't the first person to recognize this uniformity in nature's processes. For example, nearly 300 years earlier, Leonardo da Vinci noted that rocks in the Italian mountains appeared as though they had been formed in the sea. But Hutton was the first to explain the principle in detail, and he is generally given credit for it. This, together with his sharp observations on geological processes in general, have earned him the title "the father of modern geology."

Where had Hutton made the observations that led to his statement of uniformity? Indoors, from his comfortable living room? Obviously not. He went into the fields, where the action is! To understand nature, we must observe it "where it's at." As a geologist once said, "Geology withers indoors." We can use some armchair geologists, but not too many.

> Go, my sons—burn your books—buy yourselves stout shoes—go to the mountains—search the valleys—the deserts—the shores of the seas—the deepest recesses of the earth. In this way, and no other, will you arrive at a knowledge of things and of their properties.
>
> Petrus Severinus (1571)

CHECK YOUR FACTS

(5)

1. What are the three main groups of rocks?
2. Describe some ways in which rocks change.
3. What is the principle of uniformitarianism?
4. What is the principle of catastrophism?

APPLYING WHAT YOU HAVE LEARNED

(6)

1. Beautiful groups of well-formed crystals had to have space in which to grow. Where do you think such crystals are formed?

2. Are any of these materials minerals?
   coal   artificial diamonds   water
   petroleum   bottle glass

(4) The battles between the Neptunists and the Plutonists were at times very bitter. For a time, the Neptunists were the "defenders of the faith" against the heretical proponents of uniformitarianism. It was easier to believe that the Creator created everything instantly, at a specific time.

(5) ANSWERS / Check Your Facts

1. Igneous, sedimentary, and metamorphic.
2. Melting, metamorphism, and weathering.
3. Nature's forces and processes are uniform and have operated over time to change the surface of the earth; they are still operating. Simply stated, the theory says, "The present is the key to the past."
4. The earth's features were the result of sudden, violent events.

(6) ANSWERS / Applying What You Have Learned

1. The best-formed crystals grow in cavities in the rock.
2. Ice is a mineral. Glass has no crystal structure, so it isn't a mineral. Coal and petroleum are made of organic molecules, and so, technically, they are not minerals. Artificial diamonds? A purist would say they aren't minerals, but an interesting discussion can come from this.

3. You know that the three main classes of rocks can be related to each other in terms of the rock cycle (Figure 2.17). Notice that some arrows on the diagram cut *across* the circle. What does *each* of these particular arrows tell us about the rock cycle? What do all of these cross-cutting arrows, considered *together*, tell us about the rock cycle? Do you think the history of many rocks can be traced from magma, around the cycle, and back to magma? How would you know whether a particular rock has "gone full circle"?

4. Crystal structures are made out of ions. Two main factors control which ions can become part of the crystal structure of a particular mineral. These factors are the *electrical charge* of the ions and the *size* of the ions. The crystal structure has to be electrically neutral (have just as many positive charges as negative charges). The ions cannot be too large or too small, or else the crystal structure will be so distorted that it will not be a uniform crystalline material. Thus, if ions have about the same size and charge, they can substitute for each other in the crystal structure. The following is a list of the sizes and charges of some of the common ions:

Ionic Charge		Ionic Radius (in angstroms)
O^{--}	(oxygen)	1.32
Si^{++++}	(silicon)	.42
Al^{+++}	(aluminum)	.51
Fe^{++}	(iron)	.74
Ca^{++}	(calcium)	.99
Na^{+}	(sodium)	.97
K^{+}	(potassium)	1.33
Mg^{++}	(magnesium)	.66

Which two ions have the same charge and about the same size? What pairs of ions are approximately the same size, but have different amounts of charge?

Olivine has the general formula $(Mg,Fe)_2SiO_4$. Why do you suppose Mg and Fe are within the brackets? One type of olivine has the formula Mg_2SiO_4 and another type has the formula Fe_2SiO_4. Most olivines contain both Mg and Fe, with Mg usually dominant. Are these three olivine formulas electrically neutral?

Plagioclase feldspars are more complicated. One type has the formula $NaAlSi_3O_8$ and another type has the formula $CaAl_2Si_2O_8$. There are several types with both Ca and Na ions

3. There are many shortcuts in the cycle. For example, a metamorphic rock can be weathered and may never be melted. Together, the arrows emphasize the importance of change and the many different courses nature can take. We can't tell if a rock has gone "full cycle," for once it is melted evidence of former textures is eliminated. However, chemical compositions of magmas may tell us which rock was melted. New isotopic methods provide new clues.

4. (*a*) Fe^{++} and Mg^{++}; Ca^{++} and Na^{+}; Al^{+++} and Si^{++++}. (*b*) Mg and Fe are within parentheses (brackets) to show that they can substitute for each other. (*c*) Yes, each olivine type has eight negative and eight positive charges. Moreover, Ca and Na substitute for each other even though their charges are different. Both formulas are electrically neutral, with sixteen negative and sixteen positive charges. When Ca and Na substitute for each other, an Al replaces a Si, thus neutralizing the total charge.

Note: In actuality, a mineral grain may not be neutral because of unsatisfied charges on the edges of the broken grains.

present. In fact, all ratios of Ca and Na can be found. Thus, can't Ca and Na ions substitute for each other? Are they about the same size? Do they have the same charge? Are both formulas electrically neutral? What other substitution has to take place when Ca and Na substitute for each other in plagioclase?

KEY WORDS

electron (p. 22)
nucleus (p. 22)
proton (p. 22)
neutron (p. 22)
atomic number (p. 22)
shell (p. 22)
angstrom (p. 24)
ion (p. 25)
crystal structure (p. 25)
crystal lattice (p. 25)
crystalline (p. 25)
halite (p. 25)
element (p. 26)
compound (p. 26)
ionic bond (p. 26)
covalent bond (p. 26)
mineral (p. 27)
crust (p. 27)
silicate (p. 31)
tetrahedron (p. 31)
cleavage (p. 31)
igneous (p. 34)
sedimentary (p. 34)
metamorphic (p. 34)
magma (p. 34)
lava (p. 35)
strata (p. 35)
stratum (p. 35)
rock cycle (p. 36)
atmosphere (p. 36)
composition (p. 37)
texture (p. 37)
uniformitarianism (p. 38)
catastrophism (p. 38)

Figure 3.1 These volcanic rocks formed from a lava flow on the side of Mt. Vesuvius, near Naples, Italy.

Introductory Demonstration

The growth of alum crystals is fascinating to watch. Try this at home at first to get the technique and then demonstrate to your class. You can buy alum at the drugstore. Make a super-saturated solution of alum by stirring it into warm water until no more dissolves. Then make some seed crystals by evaporating some of the solution. Take a well-formed seed crystal, tie it to a thread, and suspend it in a quart jar of the solution. A large crystal should result in a few days. Interested students may want to grow these crystals at home.

chapter 3

Igneous Rocks

Imagine that you are standing near an erupting volcano, feeling the heat, smelling the foul gases, hearing the explosions, and seeing the bubbling, red-hot lava. Wouldn't you wonder what depth the lava came from? Or why it came to the surface? Or why it's hot? Or how much more molten rock is down there? In order to answer these questions, geologists study both modern volcanoes and old volcanic rocks. They know that the present is the key to the past.

WHAT HAPPENS TO MAGMA?

Rocks formed when magma extrudes (comes out) to the surface are called **volcanic** or **extrusive rocks**. The lava flow shown in Figure 3.1 is an extrusive rock that formed when the lava cooled and crystallized. But not all magma comes to the

surface. Some magma forces its way into or intrudes into existing rocks, forming **plutonic** or **intrusive rocks** (Figure 3.2). Plutonic rocks are named after Pluto, the Greek god of the underworld. We think that some magma crystallizes into rock very deep beneath the surface, as deep as 20 kilometers.

But can geologists, when studying plutonic rocks, use the present as the key to the past? Where could they observe magma that is cooling at depth? Even if they could get down there, could they live at the high temperatures and pressures? True, they study exposed plutonic rocks in the field, but this does not answer all their questions. If they are trying to answer certain questions about how these rocks formed, they must use different methods.

Geologists use strong "bombs" or containers in which they create high temperatures and pressures, similar to those that exist at depth. By placing certain ingredients in the bombs, melting them, and cooling them, they try to reproduce nature's results. (For example, they might try to produce artificial igneous rocks in the bombs.) Do they succeed? They think they do, sometimes. One of the biggest problems is that it is impossible to duplicate the length of time. If it takes a large body of magma a thousand or a million years to cool, how can scientists duplicate this in the laboratory?

Figure 3.2 The light-colored bands are plutonic rocks intruded between other (darker-colored) rocks.

Texture. The main clue to the environment in which an igneous rock crystallized is the *size of its crystals.* If the crystals in an igneous rock are small, this means that the magma cooled quickly, before the crystals had time to grow very large. (The ions in the magma didn't have time to gather and form large crystals.) Where should magma cool most quickly? At the surface, where cool air and water are present, or deep in the crust, where it is hot and where the surrounding rocks help to keep the heat in the magma? Obviously then, extrusive rocks contain small crystals and intrusive rocks contain larger crystals. However, couldn't a thin sheet of magma that cooled underground be fine-grained, and a thick lava flow have large crystals in its center? (1)

(1) Certainly, a thin sheet of intrusive magma could be fine-grained, and a thick lava flow could be coarse. Thus, hand specimen identifications could sometimes be wrong as to depth of cooling, but the study of the rock units in the field would clearly show whether they were intrusive or extrusive.

activity 3.1 Growing crystals

We can't watch crystals forming in magma, but we can watch them forming in the chemical compound called thymol. For this experiment you need thymol, a petri dish, a hot plate, a microscope (preferably a binocular microscope), and forceps.

***Caution:* Although thymol is not poisonous, it can irritate the skin. Handle it with care.**

Put a small amount of thymol in a petri dish and heat it on a hot plate at the lowest heat setting. When the thymol is completely melted, transfer the dish to the microscope stage. Add a few small crystals to the melt to act as nuclei or "seed crystals" on which the material will easily crystallize. (2)

As the melt cools, watch the crystals form. How are they growing? Make a sketch of the crystallized material.

Try cooling the melt rapidly (on an ice cube) and slowly, without seed crystals. (It may be harder to observe the crystalization under the microscope in these cases, but the final crystalline materials can be compared.) What are the differences? What effect does the rate of cooling have on crystal size?

(2) Melting the thymol on a clear watch glass and then observing it under a binocular microscope with a black stage works best. The same thymol can be used several times. Make sure every student actually observes the crystallization, as it is rather dramatic.

What do you think happens when magma cools so quickly that the ions can't move through the magma and can't get together to form any crystals? If you concluded that *obsidian*, or natural glass, forms, you were right. What is the arrangement of the ions within the glass? And here's another brain- (3)

(3) The ions, of course, are unordered and in no definite crystalline lattice. Glass is a supercooled liquid. Glass in very old window panes has been found to be thicker at the bottom of the pane and, occasionally, has flowed over the wood beneath.

stretcher for you: What texture should result if magma cools slowly at first, and then more rapidly? What can you say about the rate of cooling of the magma when the rocks pictured in Figures 3.3 and 3.4 were formed?

(1) **(1)** If a magma cools slowly and then rapidly, the resulting rock may have earlier large crystals in a matrix of later fine crystals. Crystal size may not necessarily be related to time only—if a magma loses its gases, the remaining liquid will be more viscous, and ions will not be able to move through the thicker magma to form large, growing crystals as easily as before. Therefore, many smaller crystals will result. Likewise, the very large crystals mentioned at the beginning of Chapter 2 grew in a very watery melt, actually in the residual liquids of crystallizing magmas. These rocks, composed of very large crystals, are known as "pegmatites."

Composition. Igneous rocks vary not only in grain size, but also in composition. All magmas are solutions of water and ions of silicon, aluminum, iron, magnesium, calcium, potassium, and sodium. Other ions are also present in small quantities. Magmas that contain much silicon and a relatively large amount of potassium and sodium are often described as **granitic magmas**. They form granitic rocks—that is, they form granite or rocks whose compositions are more or less similar to the composition of granite. Magmas that contain relatively more iron, magnesium, and calcium are called **basaltic magmas**. They form basaltic rocks—basalt or rocks similar to basalt. Basaltic rocks are generally dark grey, dark green, or black—an effect produced by the higher iron and magnesium content. Granitic rocks tend to be light-colored. Of course there are also magmas with compositions between the granitic and basaltic types.

CHECK YOUR FACTS

1. What two general types of rocks are formed from magma?
2. What does crystal size tell you about an igneous rock?
3. What is the difference between granitic and basaltic magmas?

(2) **(2) ANSWERS** / Check Your Facts

1. Extrusive and intrusive (plutonic).
2. The rate of cooling (small crystals, rapid cooling).
3. Granitic magmas contain much silicon and a relatively large amount of potassium and sodium. Basaltic magmas contain relatively more iron, magnesium, and calcium.

KINDS OF IGNEOUS ROCKS

You should keep in mind that igneous rocks range in composition all the way from granitic to basaltic. The terms "granitic" and "basaltic" are not precise. They just indicate the rock composition in a general way. The variation in the mineralogical composition of igneous rocks is shown in the diagram at the top of Figure 3.3. Orthoclase, for example, is found at the left of the diagram, extending to about the middle. It is found in granitic and in some intermediate rocks. Olivine is found at the right of the diagram. It is found in basaltic rocks. Plagioclase is found in granitic, intermediate, and some basaltic rocks. The only rocks plagioclase is not found in are

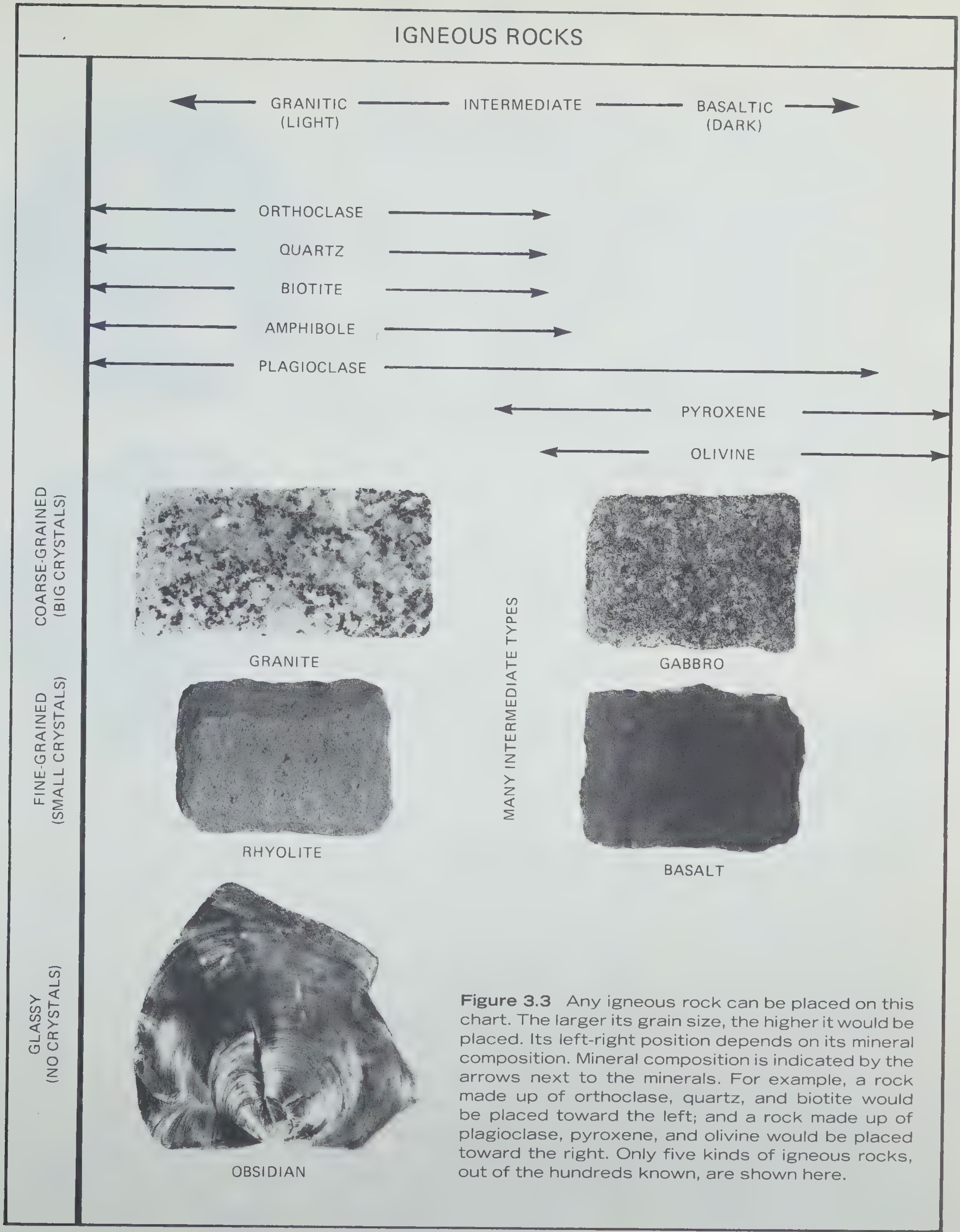
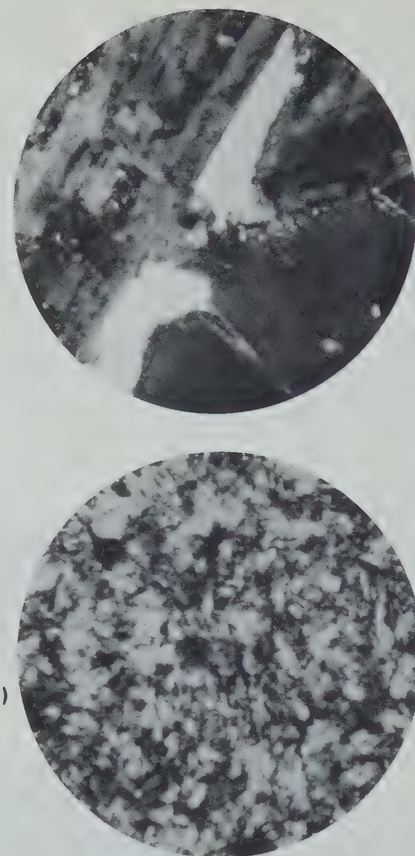


Figure 3.3 Any igneous rock can be placed on this chart. The larger its grain size, the higher it would be placed. Its left-right position depends on its mineral composition. Mineral composition is indicated by the arrows next to the minerals. For example, a rock made up of orthoclase, quartz, and biotite would be placed toward the left; and a rock made up of plagioclase, pyroxene, and olivine would be placed toward the right. Only five kinds of igneous rocks, out of the hundreds known, are shown here.

the rocks at the extreme right of the diagram. Such rocks are extremely rich in iron and magnesium minerals, mainly pyroxene and olivine.

Over 600 igneous rocks have been named! The five rocks shown in Figure 3.3 are well-known kinds. Two of them, granite and basalt, make up about 95 percent of the igneous rocks in Earth's crust. (There is a layer of basalt over the entire Earth. The continents consist mainly of a layer of granite lying on the worldwide layer of basalt.) Because granite and basalt are so common, we won't bother with the rest of the igneous rocks. They can't be too important, can they? Interestingly, rocks brought back from the Moon have all been basaltic. On the other hand, the first tests of materials on the surface of Venus have shown that the materials are granitic! (The tests were done automatically by unmanned spacecraft that landed on Venus. The results of the tests were sent back to Earth by radio.)

What can you say about the rate of cooling of the magma when the rocks pictured in Figure 3.3 were formed? Granite and rhyolite have very similar compositions but differ in grain size (Figure 3.4). Which rock cooled faster?



(1)

Figure 3.4 These are microscopic views of granite (top) and rhyolite (bottom).

(1) Rhyolite

activity 3.2 Identifying rates of cooling in igneous rocks

Your teacher will provide you with some specimens of igneous rocks. Arrange them into the following groups:

1. **Those that appear to have cooled very rapidly.**
2. **Those that appear to have cooled rapidly.**
3. **Those that appear to have cooled slowly.**
4. **Those that do not appear to fit into any of the above groups.**

Why are there magmas of different compositions?

We said on page 46 that there are magmas of different compositions. If different kinds of rocks are melted in the crust, wouldn't they form different magmas? Wouldn't melted clay, melted granite, and melted basalt be quite different chemically? Surely different magmas can be formed in this way.

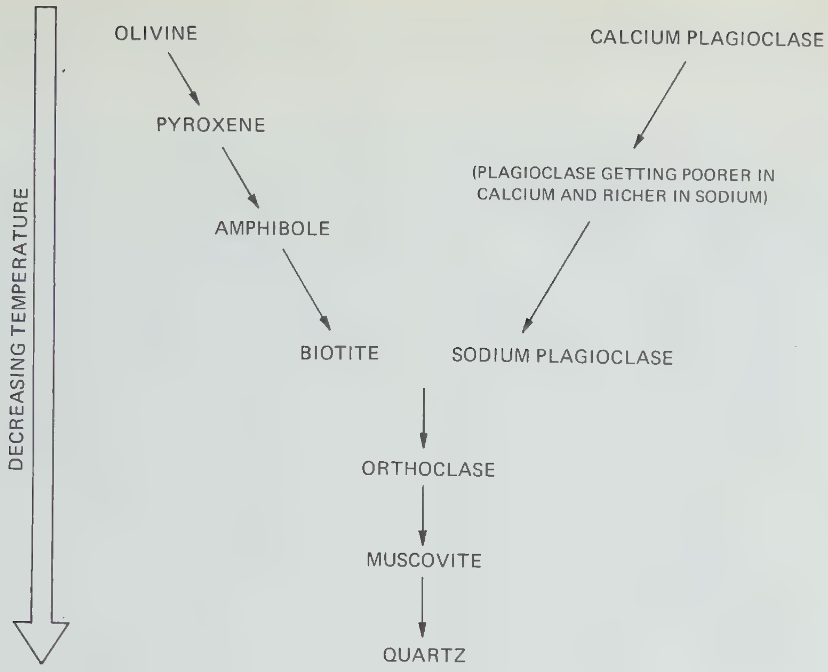


Figure 3.5 This diagram shows the order of crystallization of minerals in a basaltic magma with decreasing temperature. Complicated reactions may go on between the minerals at the left of the diagram.

According to another theory, proposed by the geophysicist Norman L. Bowen, the most common type of magma is basaltic. He suggested that most magmas are originally basaltic, and that other types of magmas come from them. In the Geophysical Laboratory in Washington, D.C. (known affectionately to some as the "Gee-Whiz Lab"), Bowen observed what happened as basaltic magma cooled. He found that olivine and calcium plagioclase were the first main minerals to form in this magma. He also found that if the first crystals of olivine are left in the cooling magma, some will react with the magma and form pyroxene. The resulting rock will then be made up of plagioclase, pyroxene, and olivine. (What kind of rock would this be? Refer back to Figure 3.3.) If the olivine is removed from the magma, something else happens. Suppose the olivine crystals settle to the bottom of the body of magma. Then the magma can't react with the olivine, and the magma changes in composition. You know from the mineral compositions (Table 2.2) that olivine contains iron and magnesium. So if olivine is removed, doesn't the magma become poorer in iron and magnesium? And doesn't it become relatively richer in the remaining elements? If each mineral is removed from the magma as it forms, the magma composition will continually change. Finally, the remaining magma is granitic in composition, and when it crystallizes, mostly orthoclase and quartz are formed (Figure 3.5). In this way, a small amount of granitic magma can be formed from a basaltic magma. (If this (2)

(2) The details of crystallization of a basaltic magma are complicated. This bit is included here to show some of the complexities of scientific investigation. Even if students don't understand this paragraph, just move on—don't belabor the issue.

granitic magma cools beneath the surface, what rock does it form? If it reaches the surface as lava, what rock does it form?) The process in which different magmas are derived from one original magma is called **magmatic differentiation**.

Few, if any, geologists question Bowen's results. But many doubt whether his theory can explain all the different igneous rocks in the world. If Bowen's theory is the only explanation, then why are the continents mainly granitic and the ocean floors mainly basaltic? Shouldn't the different rocks occur together more commonly if they crystallized out of the same blobs of magma? Why aren't the intermediate rock types more common?

A major objection to Bowen's model of magma differentiation is that there is too much granite on Earth. Only a small amount of basaltic magma ends up as granite (less than ten percent), whereas 95 percent of the continental crust is granite. The fact that Earth has so much granite is considered by some geologists one of the greatest unsolved problems in earth science. When this problem is solved, we shall know far more about not just granite, but the history of the entire Earth—how it was formed, what happened to it in its early stages, how it acquired its internal structure and its crust.

CHECK YOUR FACTS

1. Are all igneous rocks either granitic or basaltic in composition? Are there distinctly different kinds of igneous rocks, or is there a continuous variation from kind to kind?

2. What is an obvious, visible difference between granite and rhyolite, and between gabbro and basalt?

3. How might a basaltic magma yield different kinds of magma?

(1) (1) **ANSWERS** / Check Your Facts

1. No. Yes, but there is also continuous variation from kind to kind.
2. Texture (grain size or crystal size).
3. By magmatic differentiation.

IGNEOUS MINERAL RESOURCES

Do you know why nations wage wars? There are many reasons, of course, but one of the important reasons is mineral resources. If a piece of land contains deposits of important minerals, then other nations may want that piece of land.

Mineral resources have helped empires to grow and become great. Today they may determine whether a nation can

be an important industrial country. International politics are often based on mineral resources. (Perhaps there should be a special branch of geology dealing with "geopolitics"!) Who is going to be able to buy the oil of the Middle East? Who is going to control the rich agricultural "bread baskets" of the world? If oil is found 10 kilometers offshore, does it belong to the nation off whose shore it is found? At what distance from the shore should the sea become international territory rather than national territory?

Mineral deposits have been formed in many ways. Igneous, sedimentary, and metamorphic processes have all been important in their formation. You probably think that deposits of metallic compounds—compounds of iron, copper, silver, and all the rest—are the most valuable mineral resources. Actually, the value of nonmetallic deposits, including the fossil fuels (oil, gas, and coal) is three times that of metallic deposits.

Natural concentration of the different elements is necessary before a resource is valuable. For example, copper makes up only 0.00005 percent of Earth's crust. How many times richer in copper does a rock have to be to form ore containing 0.25 percent copper? How many times for ore of 1 percent copper? It is lucky for us that igneous, sedimentary, and metamorphic processes have concentrated elements enough to make it worthwhile for man to mine them. Now let's study some of the important igneous mineral resources.

Nickel. The world's largest nickel mine is at Sudbury, Ontario, Canada, in a basin-shaped body of dark-colored, coarse-grained igneous rocks. It produces as much copper as nickel, and fair amounts of platinum, gold, silver, selenium, and tellurium as well. The ore is made up of heavy sulfide minerals. These minerals may have settled out of the magma after they were formed and collected at the bottom of the magma pool. Geologist Robert Dietz thinks that the Sudbury ore body may have a different origin than that just described. He suggests that a meteorite about 4 kilometers in diameter hit the Earth at Sudbury. It was a copper-rich, nickel-and-iron meteorite. The great heat caused by the impact melted much of the meteorite and the surrounding rocks producing the magma that crystallized to form the igneous rock. Large reserves of low grade copper and nickel ore have also been found in gabbro in northeastern Minnesota, but they are not yet being mined.

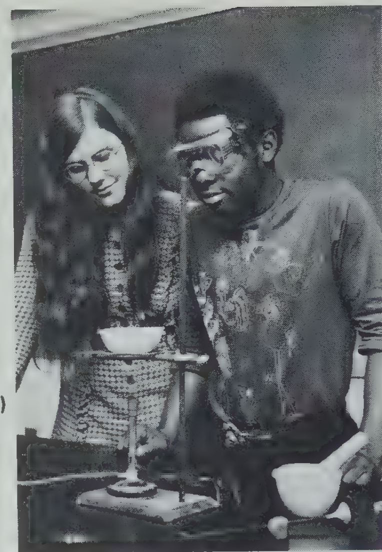
activity 3.3 Extracting lead from its ore

The metallic element lead (Pb) is found combined with other elements. For example, it is found in combination with sulfur as the mineral galena (lead sulfide, PbS). To obtain lead, it must be extracted from galena. For this activity you need a few grams of galena, a porcelain crucible supported on a ring stand or tripod by a clay triangle or wire net, a bunsen burner, a charcoal block, and a blowpipe.

Crush a few grams of galena and place in the crucible. Heat strongly. What does the gas that is released smell like? What do you think it is? (1)

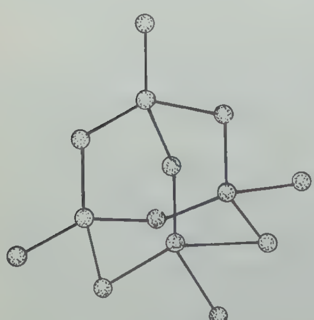
Remove some of the "roasted" ore from the crucible and place in a cavity in the charcoal block. Direct the flame of the blowpipe into the ore until small beads of metallic lead are formed. What has been happening?

Operations similar to these are used in the extraction of metals from sulfide minerals (minerals composed of a metal and sulfur).

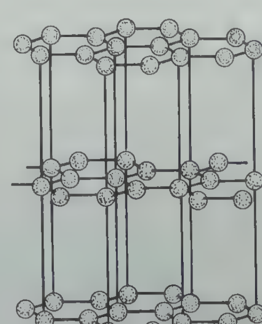


(1) This activity is a bit tricky—try it yourself first. Make sure the galena is crushed and ground to a very fine powder or it will decrepitate and fly all over. Have students wear safety goggles while heating the powder. Use the mineral stibnite (Sbs) if it is available; it works much better than galena. Galena is suggested here because it is more common, but stibnite gives off more gas (SO_2), and the metallic beads form easily.

Diamond. One of the most beautiful and costly gem minerals is diamond. It is a crystalline form of the element carbon. The diamonds of the world originally all came from small igneous intrusions called diamond pipes. Some pipes are only 30 meters in diameter. Diamond pipes are composed of igneous rock very rich in iron and magnesium minerals, such as pyroxene and olivine. The diamond-bearing magma probably came from a depth of 100 to 160 kilometers. Some geologists think that the diamonds crystalized at great



DIAMOND



GRAPHITE

Figure 3.6 Diamond and graphite (left) differ in the arrangement of their ions.

Figure 3.7 This copper mine in Utah (right) is about 800 meters deep. The ore minerals were deposited by hydrothermal solutions.

depths and were somehow transported upward. A bit of evidence for this idea is that two broken parts of a diamond were found at different levels in one mine. And they fitted together perfectly! Diamonds are rare even in the highest grade ore. One carat (about 0.2 gram) for each three tons of rock, or 0.0000073 percent, is the best ore ever mined. Actually, most diamonds (96 percent) are mined not directly from the rocks in which they were formed, but from sediments that were formed by the weathering and erosion of those rocks.

The African continent produces 97 percent of the world's diamonds. The largest diamond ever found, the Cullinan diamond from the Republic of South Africa, measured 3106 carats (almost 0.6 kilograms or 1.3 pounds)! Only one diamond pipe—at Murfreesboro, Arkansas—has been found in North America. However, a few diamonds have been found elsewhere in the United States in gravel deposits. Some diamonds have been found in sediments carried south from Canada into the United States. Anyone for going to Canada to look for the lost diamond pipes?

The best diamonds are so valuable that you could hide more than $10,000,000 worth of them on your body; that much gold would weigh about 10 tons. Only about 20 percent of the diamonds mined each year are of gem quality. Most are used by industry in cutting tools, since diamond is the hardest mineral known. Graphite, one of the softest minerals, is pure carbon just as diamond is. They are different because the ions are loosely packed and bonded in graphite and tightly packed and bonded in diamond (Figure 3.6). Industrial-quality diamonds can now be manufactured by subjecting graphite to pressures of 100,000 atmospheres and temperatures of 15,000°C.

Figure 3.8 A quartz vein.

Hydrothermal ore minerals. As a body of magma crystallizes there are commonly hot, watery solutions left over. These **hydrothermal solutions** often contain ions of silver, gold, copper, zinc, and lead. These ions are not found in the crystal structures of the common rock-forming minerals because their sizes and charges are wrong for the crystal structures. The hydrothermal solutions commonly find their way into the rocks around the magma and form veins and scattered spots of ore. The copper in the electric wires in your home may have come from the hydrothermal copper deposit shown in Figure 3.7. Some hydrothermal quartz veins contain

gold. Prospectors and geologists always check white quartz veins (Figure 3.8) very carefully; that's why so many of them have holes in the knees of their pants!

CHECK YOUR FACTS

1. What is the difference between magma and lava? (1)
2. What does the size of the crystal grains in an igneous rock tell you about the rock's history?
3. What are the two most abundant igneous rocks?
4. What is magmatic differentiation?
5. What is a hydrothermal vein?

(1) ANSWERS / Check Your Facts

1. Magma exists under Earth's surface; when it escapes to the surface it is called lava (cf. Chapter 2). (Lava has also lost some of the gases present in the magma.) Magma is the molten rock below the surface; it contains most or all of the ingredients present under the surface.
2. Whether it cooled slowly.
3. Granite and basalt.
4. See pages 49 and 50.
5. A vein of mineral derived from a hydrothermal solution. This is a hot, watery solution of various metallic ions, which usually crystallize out into veins and spots of ore.

APPLYING WHAT YOU HAVE LEARNED (2)

1. Many of the Indian arrowheads found in the western United States are made out of obsidian. The arrowheads are made by flaking or chipping the obsidian. Why was obsidian so widely used for this purpose by the Indians?

2. Gold has an ionic radius of 1.37 angstroms and a charge of +1. Silver has an ionic radius of 1.26 angstroms and a charge of +1. You've read about hydrothermal gold veins. Do you think any of these veins could contain silver with the gold?

3. We know that if a magma cools slowly, the crystals can grow large because there is much time for the ions to move through the magma to become part of a growing crystal. What if a scientist proved by some new technique that a certain very coarse-grained igneous rock was formed from a magma that cooled relatively quickly? How could the coarse crystals be explained?

(2) ANSWERS / Applying What You Have Learned

1. Obsidian has no crystalline structure, and therefore it breaks with a curved or conchoidal fracture. Chert breaks in the same way and is also used for arrowheads.
2. Yes—many deposits of native gold contain native silver mixed in. If the silver content is high, the gold is "whiter."
3. This question pursues the same train of thought elaborated upon in annotation (1) on page 46. The viscosity can be as important a factor as time, and a watery magma can result in large crystals.

KEY WORDS

volcanic rock (p. 43)
extrusive rock (p. 43)
plutonic rock (p. 44)
intrusive rock (p. 44)
granitic magma (p. 46)
basaltic magma (p. 46)
magmatic differentiation (p. 50)
hydrothermal solution (p. 54)

Figure 4.1 These cracks in granite have been widened by mechanical and chemical weathering.

Introductory Demonstration

Show the filmstrip, "Sedimentary Rocks" (W).

chapter 4

Sedimentary Rocks

A man died in New England in 1826. His family had a beautiful, polished-rock tombstone put on his grave. "It shall last hundreds and hundreds of years as a memorial to this fine man," they said. Today the engraved inscription on the tombstone cannot even be read. Why not? The rock has rotted and crumbled. It had been stable beneath the surface of Earth at high temperatures and pressures, but was unstable at the surface.

WEATHERING

The alteration (change) of rocks and minerals at Earth's surface is called **weathering**. This is a logical name, because the changes are caused by the weather—by air and water. There are two types of weathering, **mechanical** and **chemical**; usually both are taking place at the same time.

Mechanical weathering. Mechanical weathering is simple to understand. It is just the breaking up of rocks and minerals into smaller pieces. Many things help break up the rocks. Trees and other plants send their roots into cracks in rocks; the root pressures commonly get strong enough to wedge the rocks apart. Particles carried by water, wind, and ice also help break up rocks. Animals burrow and help break up rock. Man himself does a pretty good job of it when he builds roads and dams. Some plutonic rocks expand and crack when the overlying rocks are eroded away and the pressure on the rock decreases. But the main cause of breaking is the freezing of water in cracks (Figure 4.1). Water expands by about 9 percent when it freezes. If water accumulates in a crack, it freezes at the top first. As the rest freezes, it puts a tremendous pressure on the rock. Pressures up to 2000 atmospheres have been recorded! And very thin films of water can get into very fine cracks, there to freeze and expand.

A pressure of 2000 atmospheres is equal to about 200,000,000 newtons per square meter or 30,000 pounds per square inch.

Chemical weathering. Chemical weathering includes all the chemical changes that result when water and air attack the rocks. Water usually contains various chemicals in solution—that is, it contains various ions. These chemicals react with rocks and break them down. Air attacks rocks chemically because it contains water vapor and, especially in industrial areas, it contains various corrosive gases.

Water and air can attack only the surface or outside of a solid piece of rock. That's why the mechanical breakdown into smaller pieces is so important. As the pieces get smaller, there is more and more total surface area to be attacked.

activity 4.1 Surface areas produced from a one-meter cube

For this experiment you do not need any lab equipment. You need only paper, pencil, and your head.

Imagine a cube of rock one meter on each edge (Figure 4.2a). What is its volume? What is its surface area? Suppose you cut it down the middle, as in Figure 4.2b. You have created two new surfaces, each of them one square meter in area. The volume remains the same, but the surface area has increased from 6 square meters to 8 square meters. If you make three such

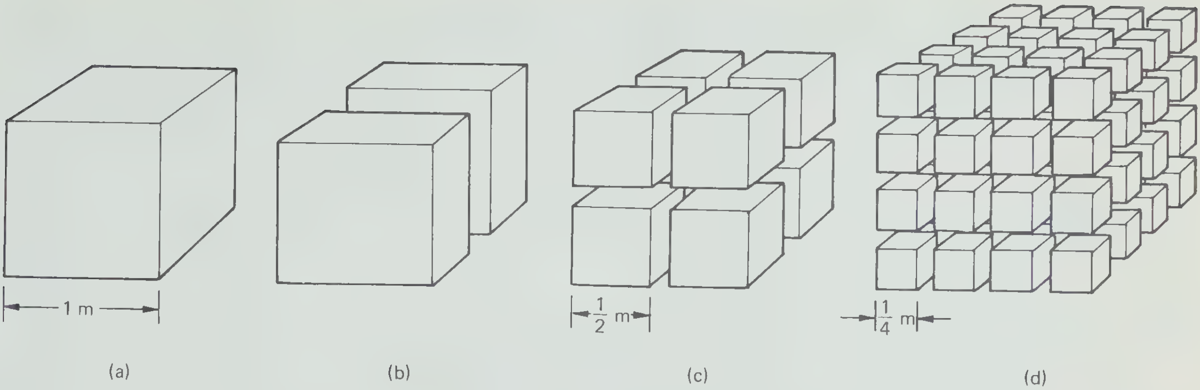


Figure 4.2 Cutting a cube.

cuts, you will obtain eight cubes $\frac{1}{2}$ meter on each side (Figure 4.2c). What is the total area now? (There are two ways to solve this problem. One way is to figure out the area of each cube and multiply by the number of cubes. The other way, which seems more complicated but is really easier, is to keep adding the amount of new surface created each time you make a cut.)

With nine cuts, you will break the original cube into 64 cubes $\frac{1}{4}$ meter on each side (Figure 4.2d). What is the area now? What is the area with $\frac{1}{8}$-meter cubes? With $\frac{1}{16}$-meter cubes? With $\frac{1}{32}$-meter cubes? Measure out on the floor an area equal to the answer you got for $\frac{1}{32}$-meter cubes.

Is mechanical weathering important to chemical weathering?

Ions are most active when they are in water and when the temperature is high. That's when they move around and react and join other ions. Therefore, water and air do the most chemical weathering in a moist, hot climate. If the climate is either dry or cold, as in deserts and polar areas, mechanical weathering is much more important than chemical weathering.

Oxygen from the air and from water combines with certain elements to form a mineral group called oxides. The process of combining with oxygen is called **oxidation.** Iron (Fe) is the most common element involved in this process. The iron on the surface of a grain of olivine (Fe, Mg, Si, O), for example, will combine with oxygen to form iron oxides (rust). The two common iron oxides are the minerals hematite (Fe_2O_3) and

limonite ($Fe_2O_3 \cdot nH_2O$). Fine, powdered hematite is red. Fine, powdered limonite is yellow. Because the iron that helps hold the silicon-oxygen tetrahedrons (or building blocks) together is removed, the olivine crumbles.

activity 4.2 Producing rust

For this activity you need some iron sulfate ($FeSO_4 \cdot 7H_2O$) and a 500-milliliter flask or pint bottle with a cover.

Grind about half a teaspoon of iron sulfate to a powder. Add the powder to the flask, which should be about half full of water. Close cover and shake vigorously for five minutes. What happens?

Let the flask or bottle stand for 15 to 30 minutes. What happens? Why is the water the color that it is? If the bottle is allowed to stand overnight the colored material will settle to the bottom. What is the colored material?

What happens to an axe or knife or nail left outside for a day or two in a wet climate? If you live in such a climate, put some new nails outside for a few days and see what happens. Would you expect the same thing to happen if you lived in a very dry climate? Or in a very cold climate?

Hydrogen ions, H^+, in water can also cause minerals to break up chemically. Some H^+ ions are present in all water because a little of the water breaks up into H^+ ions and hydroxide ions, $(OH)^-$. A more important source of hydrogen ions is carbonic acid, H_2CO_3, a weak acid present in most rain and ground water. It forms when water and carbon dioxide, CO_2, combine. (The carbon dioxide comes from the atmosphere and from plants in the soil.) Carbonic acid breaks up into H^+ ions and carbonate ions, $(CO_3)^{--}$. H^+ ions attack the common silicate minerals and change them to clay minerals. In effect, they replace the positive ions, most of which are then carried away to the sea. Here is a simplified equation as an example:

$$\underset{\text{orthoclase}}{K, Al, Si, O} + H^+ \rightarrow \underset{\text{clay minerals}}{H, Al, Si, O} + K^+$$

Actually, some of the potassium ions (K^+) stay with the clay, and some silicon is removed. Sodium, calcium, and magnesium behave much as potassium does.

Do the other common rock-forming minerals undergo chemical weathering? (Don't forget what happens to iron ions.) Figure 4.3 shows the order in which these minerals weather. What about quartz? It contains no iron that can rust and no aluminum that can form clay minerals. Therefore, almost nothing happens to quartz. Most of it stays in the soil as quartz grains.

You might be thinking that weathering is dull stuff and not worth your time. One famous geologist said that "Weathering is the geologic process most important and closest to the life of man." Now why should he make a claim like that? Read on. . . .

Olivine — Calcium plagioclase

Pyroxene

Amphibole

Biotite — Sodium plagioclase

Orthoclase

Muscovite

Quartz

Figure 4.3 Minerals weather chemically in this order. (The minerals at the top of the diagram weather first.) Does this diagram resemble a diagram you studied (1) in Chapter 3? Why? (2)

CHECK YOUR FACTS

1. How does mechanical weathering occur?

2. Why is mechanical weathering important to chemical weathering?

(1) **ANSWERS** / Check Your Facts

1. When large rocks are broken into smaller rocks.
2. It exposes surface areas that are then vulnerable to chemical weathering.

(2) Yes. It helps to show the weathering cycle.

SOIL

Has it ever occurred to you how important soil is? Without soil, could you exist? Can you plant wheat or corn or rice on bare rock? Or would you even be here to plant it?

Soils are formed by the weathering of rock (Figure 4.4). Clay minerals are the most important products of weathering and are the main ingredients of a good soil. Without it, not

Figure 4.4 Weathering is slowly breaking this gabbro down and turning it into soil.

much would grow. Besides providing necessary nutrient elements to plants, clays help hold water in the soil. Soils also contain **humus** (plant matter in various stages of decay), iron oxides, quartz, and incompletely weathered mineral grains. Can you explain why these are the main ingredients in a soil? A diagram of a vertical cut from soil down to bedrock is shown in Figure 4.5.

There are many kinds of clay minerals. Clays that still contain some K^+, Na^+, Ca^{++}, Mg^{++}, and small amounts of other elements are the best kinds. They form in temperate climates that are not too hot, not too cool, not too dry, and not too wet, but just right. In hot, wet climates rock can be so thoroughly weathered that most of the ions necessary for plant growth are carried away in solution. And you already know that a cold and dry climate means little chemical weathering. We can honestly say, then, that climate is the most important factor in determining the type of clay that forms. Years ago, geologists thought that the type of rock that was being weathered was the important factor, but more recent research showed that this was not so. Not surprising, since chemical weathering of most silicate minerals results in the formation of clay.

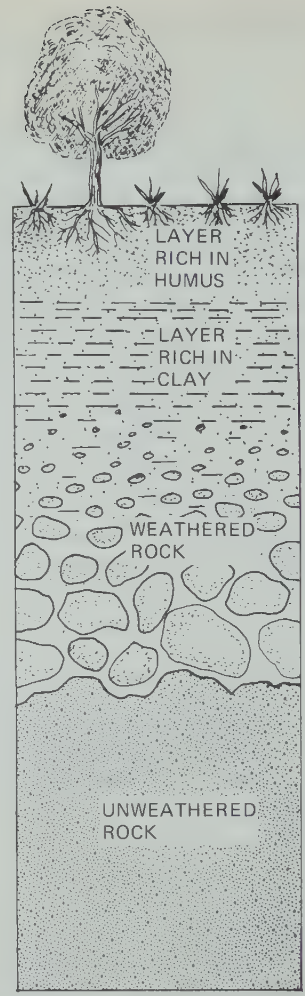


Figure 4.5 Without soil (the top layers shown), none of us would be here.

Soil conservation. Throughout history, when man has found an area of good soil he has tended to farm it for all it's worth. Also, he has commonly planted the same crop year after year. This is bad practice. Growing the same crop year after year robs the soil of certain nutrient elements, because

Figure 4.6 An abandoned homestead—a typical scene in the "Dustbowl."

each particular kind of crop tends to remove a particular set of elements from the soil. As the American pioneers moved westward, they found good soils—soils that had formed over long periods of time. They often robbed the soil of its nutrients in just a few years. Always the cry was "Westward ho!" If you ruined the land, you could move on to new land. Studies have shown that the crop yield from some types of soil dropped by half in only three years!

Man is slow to learn. In the southwestern United States in the 1930s, a combination of drought and overtilling of the land caused much of the **topsoil** to blow away, producing the famous "Dustbowl" (Figure 4.6). Topsoil is the top layer of the soil, rich in humus and in clay minerals. Even now, large tracts of land in the western states are being overgrazed —that is, too many cattle or sheep are eating the vegetation that enriches and stabilizes the topsoil (Figure 4.7). Less than a hundred years ago these rangelands were covered with grass and other vegetation that supported vast herds of bison, elk, deer, pronghorn antelope, and bighorn sheep. The establishment of cattle and sheep ranges damaged much of these choice grasslands. (1)

The depletion of our soils might be less alarming if it were happening only in some of the western rangelands. But even in Iowa, where farmers use their land carefully, the soils are losing about one percent of their fertility per year. (2)

One solution to the problem of decreasing fertility is the planting of different crops on a piece of land from year to year. Other solutions are to let the soil rest and to plow a crop

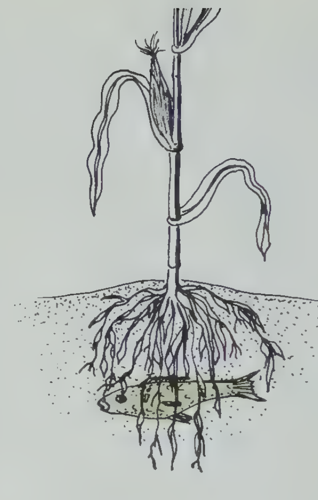
(1) Bighorn sheep are animals that we now associate with mountainous country. The pressure of man, domestic sheep, and cattle caused them to leave the grasslands for the safer, more isolated mountains. Of course, they didn't adapt that quickly to mountains—they were equally at home in either mountains or grasslands.

(2) This would be a good place for class discussions or reports on various farming or ranching practices which help preserve the soil.

Figure 4.7 Overgrazed land.

into the soil. Even with these practices, it is still usually necessary to add artificial fertilizers. (The Indians used natural materials for fertilizers. They taught the Pilgrims how to place a dead fish in each hill of corn they planted to supply the nutrients necessary for rapid growth.) It has been estimated that the agricultural production of the United States would drop 25 percent if we stopped using fertilizers.

Fertilizers are helpful, but there is such a thing as too much of a good thing! Adding so many ions that the clay minerals can't take them up for later use by plants may be harmful. Under such conditions the extra ions are carried by rainwater into streams and lakes. There algae and other microscopic plants use the nutrients and grow so fast that the water turns green with them. Bacteria that eat the plants multiply. The natural balance between plants and animals is upset. The plants choke the lake, the bacteria use up much of the oxygen dissolved in the water, and the fish and other animals that live in the lake die because there is not enough oxygen left for them. (You might argue that the plants add oxygen to the lake through photosynthesis. True, but they also use it at night when there is no sunlight for photosynthesis. So, there is only a small oxygen gain due to the plants.) In time, a clear, clean lake can turn into a muddy bog. By trying to solve one problem, man may make other problems!



Photosynthesis **is the process in which green plants, using the energy of sunlight, make food. In this process they take in carbon dioxide and water and give out oxygen.**

CHECK YOUR FACTS

1. How is soil formed?
2. What is the most important ~~mineral~~ ingredient in soil?
3. In what way can fertilizers be harmful?

(1) (1) **ANSWERS** / Check Your Facts

1. By the weathering of rocks.
2. Clay.
3. When too many are used, they can help cause the death of streams.

FROM SEDIMENT TO SEDIMENTARY ROCK

Sediment. Mechanical and chemical weathering together produce the particles we call **sediment**. Some sediment may be big boulders, some may be small pebbles, some sand-size grains, and some so small that we cannot see them without the aid of instruments. Unless the sediment is formed on an almost perfectly flat area, it will probably be moved by running water to lower elevations. Some may be moved by

wind or glacial ice or just by gravity. When sediment is finally dropped or deposited, it forms layers or beds (Figure 2.16). Most sedimentary rocks now exposed on the continents were formed in shallow seas. We know this because they contain the fossilized remains of plants and animals that lived in the sea. Similar beds are being formed today on the continental shelves (the edges of the continents covered by shallow water). Sedimentary rocks also form on the continents in lakes, along rivers, and at the foot of mountains. (2)

(2) You might ask the class why the abundance of fossils generally suggests shallow water. (Light penetration is necessary for plant growth, animals depend on plants, and so on.) But not all fossils mean shallow water—some floaters or swimmers sink to the deep sea floor when they die and are fossilized there.

In some deposits of sediment, the particles of sediment are angular bits and pieces with sharp corners. They haven't changed much since mechanical weathering broke them out of solid rock. In other deposits, the corners of the particles have all been rounded off. This happens when the particles have been hitting and rubbing against each other and against rocky surfaces while being moved. Large particles round most easily; fine particles round much less easily. The smaller particles don't hit each other hard enough to chip and round because they are so light. Pebbles and boulders, on the other hand, really wallop each other when they are being carried by waves or by a stream. Because sand is hard to round, what does sand with rounded grains tell about its history?

In a layer of sediment, part of the volume is made up of empty space between grains (the particles of sediment). The amount of space and the size of the openings between the particles is determined by many things, including variation in size and shape of the particles and the amount of pressure caused by the overlying layers of sediment. In coarse sediments without much variation in particle size and shape, water can flow between the particles quite easily.

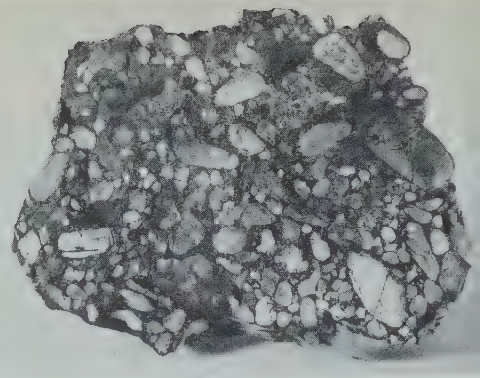
Figure 4.8 Beds of mudstone (top layer) and sandstone (lighter layer beneath).

Sedimentary rock. At what point does a layer of sediment become a sedimentary rock? For our purpose here, when sediment has been packed together enough so it's no longer just a collection of loose particles, it can be called a sedimentary rock. Quartz or calcite in solution in the water between particles can be deposited on and between the particles, cementing them together.

Like igneous rocks, sedimentary rocks can be identified by their texture and composition. A rock made mainly of clay or mud particles (less than $\frac{1}{256}$ millimeter in diameter) is called **mudstone** or **shale** (Figure 4.8). A rock made of silt particles ($\frac{1}{256}$ to $\frac{1}{16}$ mm) is called **siltstone**. What is rock made

of sand ($\frac{1}{16}$ to 2 mm) called? **Sandstone**, of course. Isn't geology logical? And finally, what is rock made of pebbles or boulders called? It's called **conglomerate** (Figure 4.9). We can't be logical all the time!

Other sedimentary rocks are the result of precipitation (the separation of solid materials out of water) rather than the binding together of loose particles of other rocks and minerals. But they are also classified in the same way—by texture and composition.



(1) **Figure 4.9** Conglomerate.

CHECK YOUR FACTS

1. What is sediment?
2. Where were most of the exposed sedimentary rocks formed?
3. How are particles of sediment cemented together?
4. Name three kinds of sedimentary rock.

(1) **ANSWERS** / Check Your Facts

1. Sediment consists of particles produced by mechanical and chemical weathering of rock.
2. In shallow seas.
3. They are cemented together when quartz or calcite in solution in water is deposited on them.
4. Mudstone, shale, siltstone, sandstone, conglomerate.

CLUES TO THE HISTORIES OF SEDIMENTARY ROCKS

Have you ever picked up a piece of rock, say a piece of sandstone, and wondered what its history was? Much history can be figured out from the minerals present and the size and shape of the particles. In the case of sedimentary rocks, the type of layering in the rock and various marks left in the layers by the ancient water currents are also very useful clues.

Remember that "the present is the key to the past." This is a very useful principle to geologists who study sedimentary rocks. Because sediment is formed, moved, and deposited by processes at the surface of Earth, geologists (and you, too) can see these things happen. We can learn about the history of a sedimentary rock by comparing it with modern sediment and with modern processes that can be more easily studied.

Water currents. The speed of a current determines the size of sediment that it can carry. The faster the current, the bigger the particles it can carry. A slow river can carry only mud (clay and silt particles); a faster current can carry silt or even sand; a really fast current can carry pebbles, or at least bounce them along the bottom. Fast mountain streams

can move even big boulders. When a strong current slows, it drops the biggest particles first and the smallest ones last. So the sizes of the particles in a sedimentary rock layer tell us quite a bit about the currents that deposited the layer.

Cross-beds. Beds of sandstone commonly contain **cross-beds** (thinner beds at an angle) within the larger beds (Figure 4.10). If the larger bed is horizontal, the cross-beds may be dipping at angles of 10 to 30 degrees to the horizontal. If you took a shovel and dug into a dry river bottom or into a modern beach or into a sand dune, you would probably find cross-beds there, too. Cross-beds can be used to tell the direction of the ancient current that deposited the layer. This helps to determine the ancient geography of the area.

Graded beds. Some beds have coarser grains near the bottom and smaller grains near the top. If there is a gradual decrease in grain size upward in the bed, the bed is said to be **graded**.

Figure 4.10 Crossbeds in sandstone.

Why should a bed be graded? There are several ways this could happen; one way is by means of a **turbidity current**. For example, when a thunderstorm hits a dry area, the stream beds are suddenly filled with torrents of very muddy water. This mixture of water with many particles of mud (and other sediment) is denser than ordinary water. When it flows into a lake or sea, it tends to stay together as one body, called a turbidity current, and it sinks to the bottom because it is denser than the surrounding water. (Pour some ink into clear water and you will see what a turbidity current looks like.) The current rushes along the bottom like a freight train (loaded with what?) until it reaches a flat area, where it slows down. What happens then? Which sediments settle first and which sediments settle last? Shouldn't this produce a graded bed?

Many scientists think that turbidity currents are important in the ocean. The turbidity currents start on the edge of the continental shelf (the shallow, relatively flat area just off the shore) and move rapidly down the continental slope (the steeper part sloping from the edge of the continental shelf down to the deep floor of the ocean). When they slow down at the base of the slope, they begin depositing graded beds. You'll look more closely into this in Chapter 10. In the following activity, you will make a graded bed.

activity 4.3 *Settling of sediments of various sizes*

In this activity you will study the different rates (speeds) at which sediments of different sizes settle. You need a heavy glass jug (preferably a big one, of several liters or of one gallon capacity) with cap; a tall, graduated glass cylinder; a watch or clock; and enough sediment to fill the jug to about 5 centimeters and have several cupsful left over. The sediment should consist of equal parts of clay, silt, fine sand, coarse sand, and small pebbles. (1)

Add the sediment to the jug and fill the jug about $\frac{3}{4}$ full of water. Cap the jug tightly and shake vigorously until all the sediment is moving. Set the jug down and observe the settling of particles. Also observe the boundaries between muddy

(1) A 1000-ml graduated cylinder (about 6 cm in diameter) works very well. You could use a natural sediment from the school grounds, but make sure it is a mixture that contains both fine and coarse particles.

water, silty water, and sandy water, and the general behavior of the currents.

About how long did it take for the nonclayey particles to settle? About how long did it take for the top centimeter of water to become semiclear (relatively clear of mud)?

After 5 minutes, how much of the water is semiclear? What size material is still in suspension in the water after 5 minutes? Would you expect it to take minutes, hours, or days for all the sediment to settle? What effect would waves have on the settling of the particles?

Formulate a general statement on the settling of particles in water, based on your observations.

Describe the sorting within the bed or layer of sediment. ("Sorting" refers to the fact that the sediments are not all mixed together but are separated, or sorted, by size.)

Note that you produced this texture more or less by "dumping" into the bottle a sediment composed of different sizes (mud, silt, sand, pebbles). How might such a bed be produced in nature? (There are several ways.)

Next, fill the graduated cylinder $\frac{3}{4}$ full of water. Take about 1 cup of the remaining sediment mixture and, aiming carefully from a point 10 to 20 centimeters above the cylinder, drop the mixture into the cylinder. Watch it settle. Describe the resulting bed of sediment after it has all settled. How might sediment be dropped into water in nature?

activity 4.4 *Sediments in lake and river water*

Go to a nearby lake or river and collect a bottle of water. Ideally, water should be collected from moving water near the shore of a lake or from the current of a river. Don't stir up the bottom sediment when collecting the samples. (Moving water from a gutter or a ditch may be substituted for water from a stream.)

Bring the water sample or samples back and let them stand quietly. How long did it take for all the sediment to settle and for the water to become clear? Is there any scum or pollution collected on top of the water?

If possible, collect samples from a river right after a heavy rain and collect samples during a dry spell. (Or from a lake right after a storm or high winds and then during a still period.) Which samples had more sediment? Why?

Pour off most of the water, evaporate the rest, and study the sediment under a microscope. What do you see?

activity 4.5 *How fast are sediments deposited?*

In this activity you will study data from a sequence of rocks in order to determine the rate of deposition of the sequence. (What do geologists mean by "sequence of rocks"?)

On the west side of the Sacramento Valley in California, a 9000-meter-thick pile of alternating layers of sandstone and mudstone is exposed. (Figure 4.8 was taken at this location.) The layers were deposited in an ancient sea, but now they are high and dry and all steeply tilted to the east (Figure 4.11). By following stream valleys that cut across the rocks, you can study the layers without climbing a 9000-meter mountain!

Many people might think that a pile of sedimentary rocks that thick must be the result of a great catastrophe in Earth's past. Let's figure out how rapidly or slowly this pile was laid down. If we know the age of the bottom and top layers, and if we know the total thickness, we should be able to figure out the rate of deposition. Right?

The fossil sea shells in the rocks have been studied, and geologists know when they lived. Also the ages of some rocks have been figured out by radioactive dating methods. (We shall discuss dating methods in Chapter 9.) The lowest beds are about 130 million years old and the youngest are about 80 million years old. A total of about 3000 meters out of the 9000 meters are graded sandstones. The rest are mudstones. Figure out how much sediment was deposited per year, on the average, using 9000 meters as the total thickness. (1)

Now assume that each graded sandstone layer was deposited very quickly by a turbidity current. Also assume that the mudstone resulted from the slow settling of mud out of the sea, which took much time. Couldn't we then ignore the sandstones in our figuring? If so, how much mud accumulated each year? How does this value for the rate of deposition compare with the value you obtained previously? (2)

Studies of the ocean floor off San Diego, California have shown that clay-silt sediment has been deposited there at the rate of 11 to 21 centimeters per 1000 years. How does this value compare with your values?

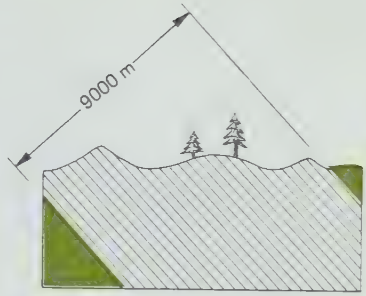


Figure 4.11 This photograph shows part of the 9000-meter-thick pile of sandstone and mudstone exposed on the west side of Sacramento Valley.

(1) 18 cm per 1000 years, or 0.18 cm per year.

(2) The answer of 12 cm per 1000 years is quite comparable to modern sedimentation rates.

Other structures as clues. Sedimentary rock layers that are even and very thin were probably deposited in quiet waters where waves and currents could not destroy them. Such beds could have been deposited in water too deep for waves to reach, or in a quiet, protected bay, pond, or lake.

Another type of bed may be meters thick and have no cross-beds or graded beds or thin beds within it. Geologists call this type of bed a **massive bed**. The origin of such a bed is a problem. How did it form? Was sediment of the same size

continuously deposited over a long period of time? Or was a large amount of material suddenly dumped in? Although such beds show no structure when examined with the naked eye, some beds show cross-beds and other features when thin slices of the rock are examined with X rays. What does this suggest about the conditions under which such beds were formed?

Some sedimentary rocks have **ripple marks** on their upper surfaces (Figure 4.12) just like those made by waves and currents in shallow water. (In what other kind of environment might ripple marks form?) Other rocks have patterns that look like the **mud cracks** and curled-up mud chips that form in dried-up mud puddles (Figure 4.13). So when we see patterns like this in rock layers, what do they tell us? Ripple marks and mud cracks are just two more of the many sedimentary structures we use to understand sedimentary rocks.

Figure 4.12 (above left) Ripple marks can be seen very clearly on these sandstone beds.

Figure 4.13 (above right) This modern mud puddle has dried up. What features, other than the geologist's hammer, would be preserved if this mud were now covered by sand, buried deeply, and became hard?

(1)(1) Ripples are also formed by wind.

Minerals in sedimentary rocks. So far we have talked about the sizes and shapes of particles, the bedding, and the sedimentary structures of sedimentary rocks. We can also learn much about the history of a sedimentary rock from the minerals it contains. A certain accent will sometimes tell us where a person is from—the Bronx, the deep South, New England, or Texas. Similarly, the minerals in a sedimentary rock will sometimes tell us where the rock came from.

In conglomerates, it is quite simple to identify the larger particles. Once we know what their compositions are, we know the type of rock or rocks that were eroded to provide the particles in the conglomerate. Coarse sandstones can be studied with a good magnifying glass. However, most sand-

stones, and all siltstones and mudstones, must be studied under a microscope if we want to find out their composition. Siltstones and mudstones generally contain small particles of quartz and feldspar, the two most abundant minerals, and clay minerals. The clays are, of course, mostly the result of weathering somewhere. It is difficult to say what kind of rock small pieces of quartz and feldspar came from, and the clays tell us more about climate than about the parent rock. Therefore rocks with this kind of composition are difficult to interpret.

CHECK YOUR FACTS

1. What is the relationship between the speed of a current and the size of sediment the current can carry?
2. How are cross-beds formed?
3. Describe one way in which a turbidity current is produced.
4. How might a thin, even bed be deposited?
5. What can the mineral composition of a rock tell us about the rock's history?

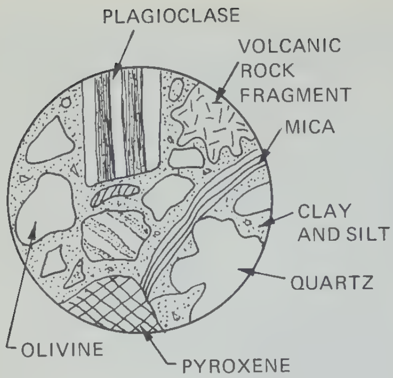
(2) (2) **ANSWERS** / Check Your Facts

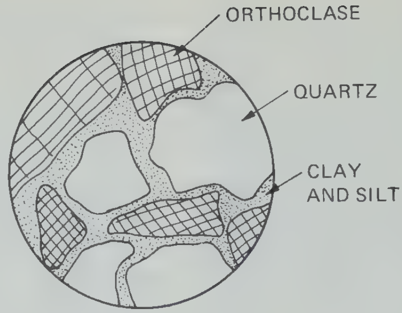
1. The faster the current, the bigger the particles.
2. When currents change direction.
3. When a thunderstorm hits a dry area.
4. When a turbidity current sinks.
5. Its original location.

SOME KINDS OF SEDIMENTARY ROCKS

Sandstones. There are so many sedimentary rocks that we can't study them all. So let's start by studying three of the main kinds of sandstone: graywacke, arkose, and quartz sandstone. Some of the names may seem strange (some are), but they are useful when discussing the rocks and their history.

Graywacke, also called "dirty sandstone," is a dark gray or greenish rock that contains many of the common rock-forming minerals, less common minerals, small pieces of other rocks, and clay minerals. The grains are of all sizes and shapes and are not rounded (Figure 4.14). Would you say that waves and currents worked on the sediments much or little? If the sediments had been worked much, the grains would be better sorted and better rounded and many of the softer grains would have been destroyed. And what does the great variation in composition of the mineral and rock grains tell us about the relative importance of mechanical weathering





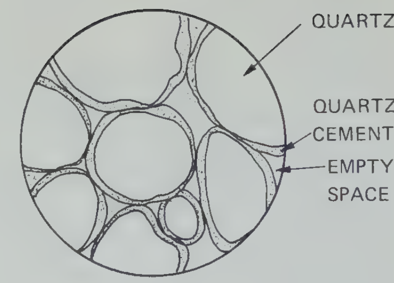


Figure 4.14 (above left) Many different minerals can be seen in this sketch of a microscopic view of graywacke. Note that the mineral grains are of different sizes and are not rounded.

Figure 4.15 (above middle) Large grains of quartz and orthoclase feldspar can be seen in this microscopic view of arkose.

Figure 4.16 (above right) Note the rounded grains of quartz in this microscopic view of quartz sandstone.

in the areas where the sediment came from? One geologist said that graywackes are like a city dump. You might even find a kitchen sink in them—especially in graywackes that are being deposited today! In many exposures of graywacke the beds are nicely graded. What does that tell us?

A sandstone that contains mostly quartz and feldspar is **arkose** (Figure 4.15). The grains are usually quite angular and poorly sorted. Cross-bedding is common. Many arkoses appear to have been deposited by rivers at the foot of high areas or mountains. In many cases they can be traced back to areas where granitic rocks were exposed but not intensely weathered by chemical processes.

The third major type of sandstone is **quartz sandstone.** Nearly all the particles are quartz, cemented by more quartz or by calcite (Figure 4.16). They are what we might call clean sandstones. The same geologist who compared graywackes to the city dump compared quartz sandstones to well-washed city streets. It is hard to say what rock the quartz grains in quartz sandstone came from. Most of the quartz grains are about the same size and are somewhat rounded. So, of all the sedimentary rocks, quartz sandstone has led the roughest life. The particles have been exposed to weathering one or more times, were beaten up in transportation, and were finally deposited in a body of water or in a lonely dune somewhere. Many quartz sandstones give indications that these processes have been repeated time and time again. With this kind of treatment, no wonder the weaker particles have been broken up or weathered away. Gone are the micas, the feldspars, the amphiboles, the pyroxenes, the olivines, and most other minerals and pieces of rock. Only the strongest and toughest particles have survived: the quartz particles. Quartz particles have certainly graduated from the School of Hard Knocks, with honors. Quartz is the stablest, both chemically and mechanically, of all the common minerals.

What happens to ions? So far we have talked only about rocks made up of particles of other rocks. What happens to the ions that are set free during chemical weathering—the Ca^{++}, the K^{+}, the Na^{+}, the Mg^{++}, and even some Si^{++++}? Some become part of clay structures, later to be used by plants. But most of these ions probably eventually get to the sea. What happens to them there?

Through time, most of the sodium has just accumulated in the sea water. The sea now contains a lot of sodium, which combines with chlorine to make sea water salty. The same is true of the potassium and magnesium. But when an arm of the sea is somehow cut off from the rest of the sea, the water evaporates. Then the ions precipitate out of solution—that is, **(1)** they come out of solution as solids and sink to the bottom. This has happened many times in the geologic past. Thick beds of sodium chloride have been deposited in Kansas, Michigan, Texas, and Louisiana. Deposits of calcium sulfate ($CaSO_4 \cdot 2H_2O$), commonly known as gypsum, and salts of potassium and magnesium have also been formed in this way.

Figure 4.17 (above) Many fossil shells can be seen in this limestone.

(1) When seawater is evaporated to $\frac{1}{10}$ of its original volume, the sodium chloride (halite) starts to precipitate.

Limestones. What about the large numbers of calcium ions that have reached the sea? Sea water contains surprisingly small numbers of these ions. So we are faced with the question, "Where did these ions go?" Give that some thought while we discuss **limestones**, which are made of the mineral calcite ($CaCO_3$).

Many limestones that were formed in an ocean contain large numbers of fossil shells, some whole and some in broken pieces (Figures 4.17 and 4.18). The shells are made of calcium carbonate. Marine animals that grow shells extract calcium carbonate from sea water to make their shells. When they die, their shells may accumulate to form a vast cemetery. The "bones" in this cemetery are buried in calcite particles derived either from broken shells or precipitated from sea water.

Many limestones look much like the other sedimentary rocks we have described. Some are thinly bedded, some are cross-bedded, and some are massive. Some limestones are very fine-grained (made of very small particles). The famous White Cliffs of Dover, England (Figure 4.19) are a thick formation of fine-grained limestone and contain many microscopic fossil shells. Plants may have played an important part in the origin of some types of limestone. Algae and other small plants cause calcite to precipitate from sea water by using

Figure 4.18 In this microscopic view of limestone, some grains are pieces of shells, and some grains are miscellaneous pieces of calcite. The rounded grain at the top is made of tiny calcite crystals stuck together; it probably formed in shallow water, where wave action helped to round it.

Figure 4.19 White Cliffs of Dover, England. Microscopic animal shells are abundant in this fine-grained limestone.

the carbon dioxide (CO_2) in the water next to them. (The more CO_2 in the water, the more calcite that can be held in solution.) Therefore it appears that nearly all limestones owe their existence, at least in part, to living organisms. As further (1) evidence of this, limestones are rare in the rock record before plants and animals became common on Earth.

There are many kinds of sedimentary rocks that we haven't mentioned. But only three kinds of sedimentary rock are really common. Mudstones or shales make up more than half of all sedimentary rocks. Sandstones make up about 30 percent, and limestone about 20 percent. That doesn't leave many percent for the other types, does it? Now *you* figure out why these three rocks are the big three. (You can answer the (2) question correctly with *one* word!)

(1) You may wonder why this book doesn't speak of two classes of sedimentary rocks—clastic and chemical—as many books do. The reason is that most limestones are clastic. The chemical class would contain only salts.

(2) The one word is weathering!

CHECK YOUR FACTS (3)

1. What are three major types of sandstone?
2. How were thick beds of sodium chloride deposited?
3. How is limestone formed?

(3) **ANSWERS** / Check Your Facts

1. Graywacke, arkose, and quartz sandstone.
2. By evaporation of shallow seas.
3. From the bodies of small, shelled animals or other living organisms.

EARTH'S SEDIMENTARY COVER

We stated earlier that sedimentary rocks cover 3/4 of Earth's land surface. This sedimentary cover is commonly only a few thousand meters thick, although in certain areas it is as much as 15,000 meters thick. (That's 15 kilometers or 9 miles!) Even so, it forms a very thin skin compared to the igneous and metamorphic rocks underneath.

Grand Canyon. The Grand Canyon of the Colorado River in Arizona (Figure 2.16) is an excellent place to study the sedimentary cover. You can see almost two kilometers of sedimentary layers exposed in the canyon cut by the river. In very few places in the world can you find so thick a pile of sedimentary layers so beautifully and neatly exposed. And, to make things even better, the river has also cut down through quite a thickness of the metamorphic and igneous rocks that occur under the sedimentary cover.

Many people have proposed to dam the Colorado River at various points near the Grand Canyon. (There are many dams on the Colorado River, but not right near the Grand Canyon.) The dams would collect water behind them to form large lakes. The lakes would have many uses. For example, people would be able to go boating, water-skiing, and fishing on them. This would bring in tourists and dollars. The water could be used for irrigation, and this would benefit the farmers. But perhaps most important of all, the dams would generate electricity, and this would bring in industry. (And jobs!) There is one hitch in this pretty picture, however. The dams cannot generate electricity forever, for all dams eventually silt up—that is, the lake behind the dams become filled with sediment. When that happens, a reservoir of mud will replace the lake behind the dam. And, of course, there will be no water to turn the turbines to generate electricity.

There is much argument as to how long it takes a lake to silt up. People who like dams say it may take thousands of years. People who don't like to see nature tampered with say that the lakes will silt up in a few hundred years at most, and probably much sooner in some cases. No one really knows the answer, because no one really knows enough about all the environmental factors involved. The study of the environment is a new science. It has not advanced very far.

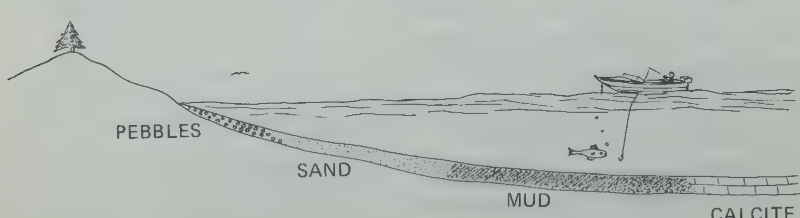
Should the Grand Canyon be dammed? The oldest rocks exposed by the cutting action of the Colorado River are over

two billion years old. These rocks and the layers above them form a beautiful record of a part of Earth from two billion years ago, a record for scientists to study, now and in the future. Should mankind, for the purpose of obtaining electricity for a few hundred years, or even for a few thousand years, bury this priceless treasure of 2,000,000,000 years? What do you think?

Lateral changes in sedimentary rocks. How far does an individual rock layer or bed extend? A kilometer? A hundred kilometers? The answer to both is "yes." Some beds cover small areas; some cover large areas. The St. Peter sandstone, an old quartz sandstone that in most places is less than 60 meters thick, is found from Minnesota to Missouri and from Illinois to Oklahoma. It was formed in shallow water near the shore of a sea. The sea kept creeping up onto the land because the land was slowly sinking. The successive shore zones merged into each other, forming a continuous layer. So, we might say that the sand bed eventually covered the entire sea floor. But we would be partly wrong. At any given time sand was being deposited only near the shore. At the same time, but farther out to sea, mud was probably being deposited. And at places in the sea where no mud and sand were carried, limestone was being deposited. So if you had been there, you probably would have seen different types of sediment at different places on the sea floor (Figure 4.20).

Figure 4.21 is a sediment map showing the distribution of modern sediment on the floor of the Pacific Ocean off the coast of Southern California. It shows that the type of sediment varies from place to place. What if all the sediment was buried and turned to hard rock? Wouldn't a geologist of the future find different rocks at different places in the same layer? These changes in sediment type from place to place within a sedimentary unit are called **sedimentary facies.** Every

Figure 4.20 At any given time, different kinds of sediments are being deposited at various distances from the shore.



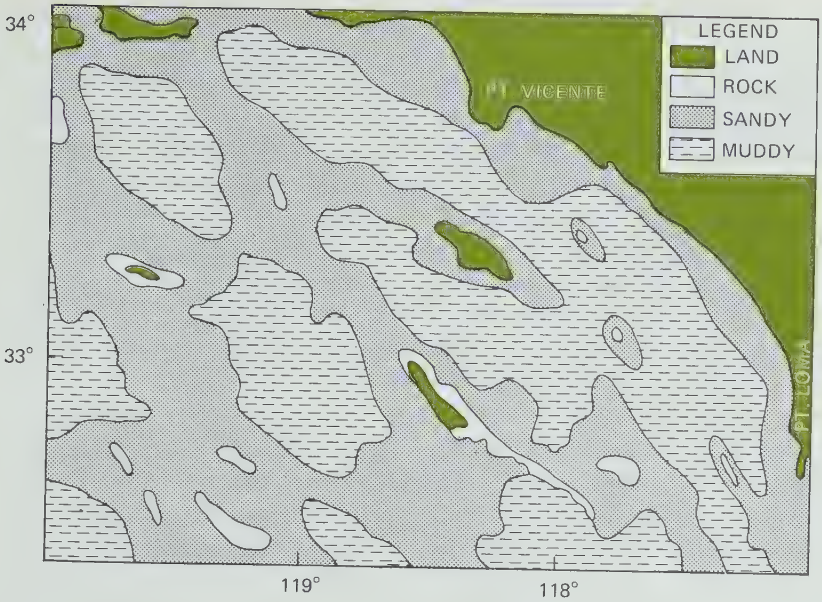


Figure 4.21 This map shows the sediments on the ocean floor off the coast of Southern California. Where do you think the sand came from? (Look closely!)

sedimentary rock layer, if it were well enough exposed so we could see it, would show such changes. Some would change in short distances, and others would change only over long distances.

The failure of early geologists to recognize this concept led to many wrong ideas of Earth history. It was simpler for them, and for us today as well, to think in terms of a bed of one kind of sedimentary rock continuing on and on. This is called "pancake" or "layer cake" geology. Unfortunately, nature generally doesn't make things that simple. Even a single layer changes from place to place. And the layers are commonly folded or broken, as you'll study in Chapter 7. Maybe nature prefers marble cakes?

CHECK YOUR FACTS

1. How thick is Earth's sedimentary cover?

2. How old is the oldest rock exposed by the Colorado River in the Grand Canyon?

3. What are sedimentary facies?

(1) (1) **ANSWERS** / Check Your Facts

1. A few thousand meters thick.
2. More than 2.4 billion years old.
3. Changes in sediment type from place to place within a sedimentary unit.

SEDIMENTARY MINERAL RESOURCES

Iron. Many valuable ore deposits are formed in sedimentary rocks by sedimentary processes. Most of the major iron ore deposits of the world were deposited as iron-rich sediments. The exact origins of these layers is a bit of a puzzle. Did primitive microscopic organisms cause iron compounds to precipitate from sea water? Were the deposits formed from iron oxide particles washed in from weathered areas? Or were both processes involved? Most of these iron formations (1) originally contained only about 25 percent iron. Later, waters moving through tiny cracks in the rocks dissolved out silica and oxidized the iron in the iron minerals, leaving the rock so rich in iron oxides that the iron percentage is 50 to 60 percent. Thus, nature concentrated the iron for us. **Hematite**, the main iron ore mineral in the Lake Superior region, provided the iron necessary for the industrial growth of the United States. About 4 billion tons of iron ore, most of it high grade, have been shipped from the Lake Superior region. (The region is connected to the Atlantic Ocean by the St. Lawrence Seaway, between Canada and the United States.) But now most of the high-grade ore is gone.

However, new methods make it profitable to mine the low-grade iron formation, a rock called **taconite**. Man has to concentrate the iron, since nature didn't do a good enough job with the taconite. The taconite is ground into very small grains, and then the magnetic iron particles (the mineral **magnetite**) are separated by strong magnets. The magnetite particles are then formed into pellets. The binder or "glue" in the pellets is a certain kind of clay that forms from the weathering of volcanic ash in Montana and other western states. About 60 percent of the Lake Superior ore shipped each year is now taconite pellets. Many new iron mines in Canada are also mining taconite. (2)

Aluminum. Another major sedimentary ore is **bauxite** ($Al_2O_3 \cdot nH_2O$), the mineral that yields aluminum. The only important bauxite deposits in North America are in Arkansas. Bauxite is formed by intense weathering of rocks in hot, wet regions. First clay (H, Al, Si, O) forms by normal weathering. If the waters have a low acidity, then the silicon (Si) is also dissolved away, leaving aluminum to combine with the oxygen and water. Thus, old bauxite deposits give us clues to the climates of long ago.

(1) Some very old iron ore deposits in Minnesota and Canada appear to be closely related to basaltic volcanism. So, here's another origin to play with!

THE HONEST MINER'S SONG

Before

(tune: Susannah)

Like Argos of the ancient times,
I'll leave this modern Greece;
I'm going to California Mines,
To find the golden fleece.
For who would work from morn till night
And live on hog and corn,
When one can pick up here at sight
Enough to buy a farm?

Chorus
Oh California! that's the land for me.
I'm going to California the gold dust for to see.

There from the snowy mountain's side
Comes down the golden sand,
And spreads a carpet far and wide
O'er all the shining land;
The rivers run on golden beds,
O'er rocks of golden ore;
The valleys six feet deep are said
To hold a plenty more.
(Chorus)

I'll take my washbowl in my hand,
And thither wind my way.
To wash the gold from out the sand
In California.
And when I get my pocket full
In that bright land of gold,
I'll have a rich and happy time:
Live merry till I'm old.
(Chorus)

(2) New processes are now being developed and used whereby nonmagnetic iron ore (hematite) is concentrated and made into taconite pellets.

(3) The Comstock Lode was the next big gold discovery.

(4) The scars left by these water jets are still visible. Also easily seen are the piles left by large dredges that worked over river sands.

(5) If you can't find the tune to the *Irish Emigrant's Lament,* notice that the tune of "Oh, Susannah!" will also do here.

(6) Panning is a bit tricky and requires a little practice, so try it yourself first. For best results, use a 9" or 10" pie pan. (Gold would be easier to pan than pyrite

Gold. We know that running water sorts sediment according to size. It also sorts particles according to weight. A current may be strong enough to carry away the lighter particles but not the heavier ones. Thus gold, which is about five times as heavy as quartz or feldspar, is concentrated in certain places in stream beds. This gold is called **placer gold**.

In 1848, Jim Marshall discovered placer gold at Captain Sutter's sawmill on the American River in California. This started the Gold Rush. From all over the world men rushed to California. Those were the days of the Forty-Niners and Clementine, when bread cost one dollar a slice and butter for it cost another dollar. Nuggets weighing as much as 88.5 kilograms (195 pounds) were found. One nugget was worth $73,710. A few struck it rich, but most just struck out.

Most of the stream gravels were panned and sifted through more than once, inch by inch. But less than ten years after the rush started, it had died, with most of the prospectors moving east to the Comstock Lode in Nevada.

Some years later, in an effort to find more gold in California, "miners" started using great jets of water to wash down thick layers of ancient stream deposits. The loosened sediment ended up ruining agricultural lands and navigation in the rivers.

Still later, the gold-bearing gravels were traced up the streams on the west side of the Sierra Nevada to their source. In this way miners discovered the gold-bearing hydrothermal quartz veins of the Mother Lode. As late as 1941, more than 175 mines were operating on the Mother Lode, but today only a few are still being worked. The total value of the placer gold and the lode gold removed thus far is more than $1\frac{1}{2}$ billion dollars.

or galena because of its much greater specific gravity.) With sand and "gold" in the pan, the pan tilted away from you, and the lowest (farthest) edge of the pan *in* a basin of water, jiggle the pan and slop some sand out of the pan into the basin. Repeat until you see a good "gold show" in the residue in the pan. Students should enjoy doing this, and it does illustrate the principles of panning for gold.

activity 4.6 Panning for gold

(6)

In this activity you will pan for certain minerals the way the miner in Figure 4.22 is panning for gold. You will need a pie pan with sloping sides; sand (as light-colored as possible); and pyrite (FeS_2) or galena (PbS) or both, crushed into sand-sized particles. (You should also have, for the next activity, a piece of quartz, a piece of pyrite, a piece of galena, and a piece

THE HONEST MINER'S SONG

After

(tune: Irish Emigrant's Lament) (5)

I'm sitting on a big quartz rock,
Where the gold is said to grow;
But I'm thinking of the merry flock,
That I left long ago.
My fare is hard, and so is my bed,
My claim is giving out,
I've worked until I'm almost dead,
And soon I shall "peg" out.

I'm thinking of better days,
Before I left my home;
Before my brain with gold was crazed,
And I began to roam.
(3) Those were the days, no more are seen,
When all the girls loved me;
When I did dress in linen clean,
They washed and cooked for me.

(4) But awful change is this to tell,
I wash and cook myself;
I never more shall cut a swell,
But here must dig for pelf.
I ne'er shall lie in clean white sheets,
But in my blankets roll;
And oh! the girls I thought so sweet,
They think me but a fool.

Figure 4.22 Panning for gold.

of feldspar—all approximately the same size, preferably 2 cm × 2 cm × 2 cm.) If you happen to have a few pieces of gold lying around, you can, of course, do the real thing!

Put about $\frac{1}{8}$ cup of sand, about $\frac{1}{2}$ teaspoon of crushed pyrite or galena, and enough water into the pie pan to fill it about $\frac{1}{8}$ to $\frac{1}{4}$ full. Mix well. Swirl the material with a circular motion until the pyrite or galena gathers at the bottom of the tilted pan, under the sand. Slowly pour off the top sand.

activity 4.7 *Specific gravities of some minerals*

In this activity you will determine the *specific gravities* of quartz, (1) pyrite, galena, and feldspar. The specific gravity of a substance is the density (mass per unit volume) of that substance compared to the density of pure water, which is exactly one gram per cubic centimeter. For example, the density of balsa (a kind of wood) is about 0.11 grams per cubic centimeter, the density of ebony (also a wood) is about 1.33 grams per cubic centimeter, and the density of mercury is about 13.5 grams per cubic centimeter. Therefore the specific gravity of balsa is 0.11, the specific gravity of ebony is 1.33, and the specific gravity of mercury is 13.5. The specific gravity of water is, of course, 1.

Partly fill a large-diameter graduated cylinder with enough water to completely cover the piece of quartz. Fill it to some convenient mark on the cylinder, for example, 50 milliliters (a milliliter is the same as a cubic centimeter). Then immerse the quartz in the water and read the level of the water again. Now you can determine the volume of that particular piece of quartz. (How?)

Next, weigh that piece of quartz (in grams). Now you can determine the density of quartz. (How?) What is its density? What is its specific gravity?

Do the same with your specimens of pyrite, galena, and feldspar. Check your figures with those your teacher has. How close did you come?

Which of the minerals used in the activity would be dropped first by a fast-moving current that suddenly slows down, assuming that all the mineral particles are the same size? Now can you explain how streams concentrate gold and some other minerals to form placer deposits?

(1) Students' results will be different from the values listed below. Why? They will be caused by errors in measurement, especially when using small pieces and/or impure materials; perhaps there will even be mathematical errors.

Mineral	*Approximate specific gravity*
quartz	2.7
pyrite	5.0
galena	7.5
feldspar	2.6
gold	15.6-19.3

You may, of course, want to have students measure specific gravities of other minerals, too.

Diamonds, other precious stones, and tin ore are also concentrated in placers. Recall that earlier you learned that 96 percent of the diamonds mined come from sediments eroded from diamond pipes. Some of these diamonds occur in placer deposits.

Coal, petroleum, and gas. Coal is a sedimentary rock derived from partially decayed plants. It formed in great swamps of the past where the incomplete decay of plants took place under water. Hydrogen and oxygen were released from the plant structure, leaving a bed rich in complex carbon compounds. Peat, a material full of undecayed plants, is the first step in the coal-making process. When peat is compressed beneath other rock layers, it becomes a higher grade coal. Coal has long been, and is still being, used as a fuel. However, Earth does not have an unlimited supply of coal; many thoughtful people feel that, rather than be burned, coal should be saved for the many valuable chemicals that can be extracted from it by advanced modern methods. Future generations may look back in amazement at the fact that we burned such a precious resource.

Petroleum and natural gas also originate from plant and animal remains. Various organic components of petroleum found in modern sediments give us the clues. Petroleum and natural gas probably formed in muds rich in organic materials and later migrated into the open spaces of sandstones and limestones. If a porous bed is capped by nonporous rock such as mudstone or shale, through which the petroleum and gas cannot move, then the petroleum and gas will be held in the porous bed (Figure 4.23). If the bed forms some type of trap so the petroleum and gas move to a certain place, then a petroleum or gas field can result. The petroleum is located between the grains of sand or in the holes dissolved in limestone by ground water. Petroleum is often called "oil." Many people probably think an "oil pool" is a big pool of petroleum in an underground cave. You now know that this just isn't true. (Don't you?)

The upfold shown in Figure 4.23 is called an *anticline.* Porous beds in anticlines are often used by oil (petroleum) companies to store natural gas. Such storage provides much more space than hundreds or thousands of man-made tanks. It's also much cheaper.

There's a story of a big company that pumped natural gas into an anticline for three years. In the meantime, a man

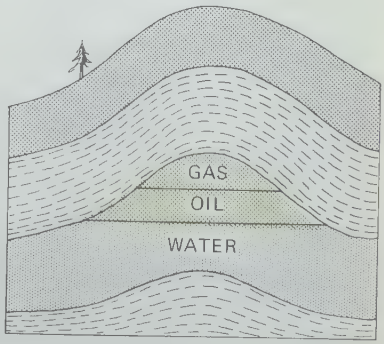


Figure 4.23 This upfold in the rocks serves as a natural storage tank. The water, oil, and gas are between sand grains in a bed of sandstone.

with a small drilling rig drilled a "wildcat" hole into a small anticline a few kilometers away. He was hoping to find oil that other drillers had missed. And guess what? No oil. But he struck natural gas instead. For two years he pumped it out, and became quite wealthy. Then one day the big company decided to check how much gas they had put into their natural storage tank. You can guess what they *didn't* find! A geologist had done sloppy work and hadn't realized that the "tank" had some "leaks" in it. The natural trap wasn't quite good enough. The gas had migrated into the other anticline through a bed of sandstone (Figure 4.24). While the company looked in vain for its gas, the geologist looked in vain for a new job.(1)

In the early days of oil prospecting, oil seeps (oil coming to the surface along cracks in rocks) were the main clue to the presence of oil beneath the surface. No one hired a geologist to look for oil. There was even a saying that "geology never filled a tank."

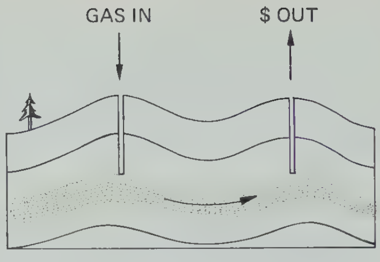


Figure 4.24 What happened to the gas?

(1) Oil seeps are natural, even on the continental shelves under sea water. But they are so small, the oil rarely bothers anything. The point is, however, that "oil spills" are not exactly new.

Figure 4.25 The Drake well.

The first commercial oil well in the United States was at Titusville, in northwestern Pennsylvania. It was drilled, almost at random, in 1859 by Edwin Drake, an ex-railroad conductor and not a professional driller (Figure 4.26). Although the Drake well was drilled to a depth of only 45 meters, it produced 400 gallons of oil a day. (In contrast, modern wells have been drilled to depths of 9000 meters. One hole in Texas reached a depth of about 8000 meters and cost about $3,000,000 to drill. And it was a "dry" hole—no oil or gas!) The Drake well started an oil boom. In the few months after Drake's lucky strike, thousands of wells were drilled, more or less at random. Some drillers grew rich but most didn't. Distilleries were set up next to the wells to remove the valuable lamp oil for burning in lamps. (Whale oil was already becoming scarce.) The natural gas was dumped as a useless by-product. Rural Pennsylvania smelled of sulfur and gas. Fumes from the distilleries filled the air. Trees were cut down and drill holes were punched down everywhere. One man described the area as "an anteroom to hell." Man certainly has long had the knack for spoiling his environment!

Eventually geologists were needed to find oil-bearing traps. Later, geophysicists (scientists with extensive training in both geology and physics) learned to locate buried traps by setting off explosive charges in the ground and detecting the shock waves reflected off the buried beds. Today, both geologists and geophysicists are necessary for finding oil, as all the easy-to-find fields have been discovered. In the United States today, there are about 240 big oil fields and 14,000 small ones. The big ones produce 3/4 of the country's oil. At the present time many new fields are being opened up on the continental shelves of the ocean basins (Figure 4.26).

Figure 4.26 Offshore drilling platforms like this are becoming common.

Today petroleum is transported in large ocean-going tankers (ships). A wreck of one such tanker can coat many kilometers of seashore with oil. Drilling on the continental shelves must be done very carefully, as oil spills can occur there, too.

Other sedimentary resources. Salt (NaCl) deposits are valuable and are found in several states. The rarer salts, such as potassium salts, are also very valuable. They are used for fertilizers and for other purposes. And gypsum ($CaSO_4 \cdot 2H_2O$), also precipitated from sea water, is used for plaster and other kinds of building materials. It is one of the world's oldest building materials.

Uranium ore is commonly found in sedimentary rocks where it has been deposited by waters seeping through the rocks. The waters originally dissolved the uranium out of igneous rocks and veins.

Let us not forget the very ordinary but very valuable deposits of sand, gravel, limestone, and shale. All are used in cement, in road building, and in other construction. Crushed rock of various types is also used to provide bulk in concrete and for road material.

We know that clay is a necessary ingredient of a good soil. It has other uses, too—for example, in ceramics, in bricks, and in paper. (Another relatively unpublicized use is in animal feeds.)

And finally, although sedimentary processes don't make water, they are directly related to our water resources. Just as some beds are reservoirs for oil and gas, many rock layers and much loose sediment provide the natural passageways and reservoirs for the movement, storage, and purification of ground water. Like soil, water is so valuable to us that its value cannot even be estimated.

CHECK YOUR FACTS (1)

1. How did sedimentary processes concentrate iron?
2. What mineral is aluminum obtained from?
3. How does the density of gold compare with the densities of most other minerals?
4. What materials do coal, petroleum, and natural gas originate from?
5. What are some dangers involved in oil drilling and transporting?

APPLYING WHAT YOU HAVE LEARNED (2)

1. We know that in a given layer of sediment or sedimentary rock there are lateral changes, as shown in Figure 4.22. Why are there such lateral changes?
2. The "muddy rocks" (mudstone and shale), sandstone, and limestone together make up more than 99 percent of sedi-

(1) **ANSWERS** / Check Your Facts

1. See page 80, the paragraph on iron.
2. Bauxite.
3. It is greater.
4. Organic materials—debris from prehistoric plants and animals.
5. Explosion, fire, destruction of arable land, oil slicks, and destruction of beaches and wildlife.

(2) **ANSWERS** / Applying What You Have Learned

1. Sorting action of H_2O on a heterogeneous mixture will deposit different sizes of grains of sediment in different places.
2. Weathering is the single word. Chemical weathering produces clay from most of the preexisting silicate minerals. Therefore shale and mudstone are very common. Sandstone is common because of the stability of granules of quartz in igneous and metamorphic rock and also because it is the end product of mechanical weathering of feldspars and other common minerals. Limestone is common because of the abundance of calcium ions freed by chemical weathering which are carried to the sea.

mentary rocks. Why are these the big three? (Remember, we said this question can be answered in one word.) But now let's get more specific. Why are mudstone and shale so common? Why is sandstone so common? Why is limestone so common?

3. Name some very important results of weathering. (Think big!)

4. Why do some minerals have greater specific gravities than other minerals?

5. What features in sedimentary rock would indicate deposition in shallow water? What features would indicate deposition in deep water?

6. Salts in sea water make up about 3.5 percent of the weight of the sea water. Evaporation of sea water produces salt deposits. This has occurred naturally in the past, and today man is purposely evaporating sea water in large, shallow ponds to obtain salt. (Salt starts precipitating when sea water is evaporated to about 1/10 of its original volume.) Evaporation of a layer of sea water 85 meters deep produces a layer of salt about one meter thick. Salt deposits that are 1000 meters thick occur in several places in the world. How much sea water evaporated to form such a thick pile of salt? How do you think this could happen?

3. Moving mountains, forming soil, providing a place for life on land. This question can be used for an open-ended discussion in which any reasonable answers are acceptable.
4. Because of the differences in atomic masses and packing volume.
5. Shelled fossils, ripple marks, mud cracks, and large scale crossbedding indicate deposition in shallow water. The absence of these features as well as the presence of fine lamination, graded beds, and lack of worm tunnels indicate deposition in deep water.
6. A pile of salt 1,000m thick would result from the evaporation of a layer of salt water 85,000m deep. Since this is improbable, it is more likely that these thick salt deposits resulted from the repeated evaporation of shallow salty water repeatedly trapped behind sandbars. Factors involved are a warm climate and a long period of time.

KEY WORDS

mechanical weathering (p. 57)
chemical weathering (p. 57)
oxidation (p. 59)
humus (p. 62)
topsoil (p. 63)
sediment (p. 64)
mudstone (p. 65)
shale (p. 65)
siltstone (p. 65)
sandstone (p. 66)
conglomerate (p. 66)
cross-beds (p. 67)
graded (p. 67)
turbidity current (p. 68)
massive bed (p. 71)
ripple marks (p. 72)
mud cracks (p. 72)
graywacke (p. 73)
arkose (p. 74)
quartz sandstone (p. 74)
limestone (p. 75)
sedimentary facies (p. 78)
hematite (p. 80)
taconite (p. 80)
magnetite (p. 80)
bauxite (p. 80)
placer gold (p. 81)
specific gravities (p. 82)

Figure 5.1 Gneiss, a metamorphic rock, often has a banded appearance, as in this sample.

Introductory Demonstration

Obtain some self-hardening clay. Leave a lump of it out in the classroom. If possible, send a similar lump to the Home Economics room and have it baked at 400° for 10 minutes. Otherwise, place the clay on a clean wire gauze and play a moderate flame on it for a while. This demonstrates metamorphic change very well—heating without melting. Introduce your demonstration by stating that the quality of a stew depends on what goes into it and how long it is cooked. Make the analogy to metamorphic rock and explain the clay as a "sedimentary rock" about to undergo metamorphism.

chapter 5

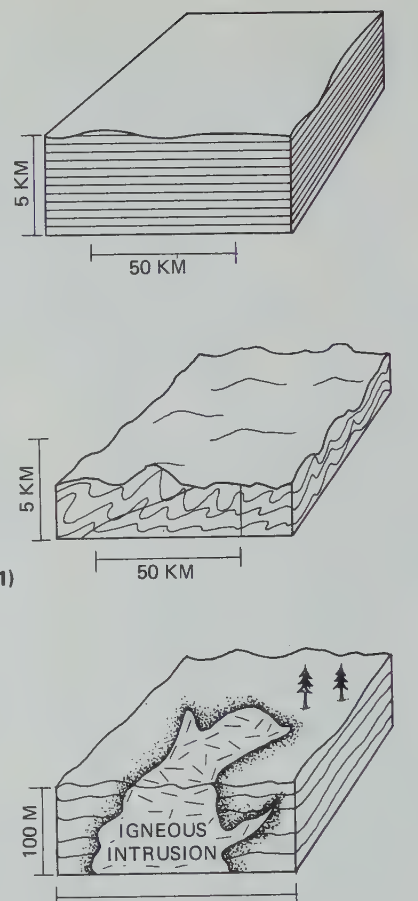
Metamorphic Rocks

"That beautiful butterfly was once a fuzzy caterpillar!" Do you remember how amazed you were as a small child, when someone first told you this? This change in form from caterpillar to cocoon to butterfly is called metamorphosis, from the Greek *meta* (change) and *morphe* (form). Most rocks aren't as pretty as butterflies (except in the eyes of geologists), but the changes that some metamorphic rocks have gone through are as spectacular as those of the butterfly!

The rock cycle tells us that change is the name of the game. (Remember the rock cycle? Look back at Figure 2.17.) Minerals that find themselves in a new environment of different pressures and temperatures and different kinds of solutions will change, or be metamorphosed. During **metamorphism,** changes occur both in mineral composition and in texture.

METAMORPHIC PROCESSES

Metamorphism happens beneath the surface, generally at depths of one to several kilometers. You may feel that weathering is a kind of metamorphism (after all, it causes a change in form), and that the cementing of a sandstone or the pressing of loose mud into a hard mudstone is also metamorphism. Strictly speaking, you are right. But geologists, by custom, restrict metamorphism to processes that occur at temperatures and pressures higher than those that normally occur at or near the surface of the Earth. Admittedly, the boundary between surface processes and metamorphism is fuzzier than the caterpillar of page 89. And at high temperatures and pressures, the metamorphic processes merge with igneous processes as melting of the rocks begins to take place. This is just one example of how difficult it is to put natural things and natural events into man-made pigeon-holes. (1)



(1) This last sentence is worth emphasizing with other examples.

Figure 5.2 Regional metamorphism (top and middle diagrams) occurs over large areas (note the scale). The top diagram shows a region of sedimentary rocks before metamorphism. The middle diagram shows the same region after regional metamorphism has taken place and the metamorphic rocks at depth have been exposed by erosion (the wearing away of soil and rocks). Contact metamorphism (bottom diagram) occurs next to an igneous intrusion and extends over a smaller area (note the scale). The intrusion and the metamorphosed zone have been exposed by erosion.

Temperature and pressure. Earth's temperature increases with depth. In a deep hole drilled in Texas, a temperature of 178°C was recorded at a depth of about 8 kilometers. What is the rate of temperature increase in the area where this hole was drilled? Studies of mines and drill holes have shown that on the average the temperature increases about 1°C for every 30 meters of depth. Some parts of Earth's crust are hotter than others, but generally everywhere it gets hotter with depth.

Let's assume for a moment that Earth's temperature increases at the rate of 1°C per 30 meters all the way to the center of Earth. At this rate, what would the temperature be at the center, which is 6400 kilometers down? Recent studies seem to show that the temperature at the center of Earth is around 4000°C or less. How does the figure you got compare with this figure? What can you conclude from this? The rate of 1°C per 30 meters is determined by measuring the temperatures at relatively short distances into Earth. Does it surprise you that this rate does not seem to apply at great depths? Think about it. Are all rates of increase uniform (that is, stay the same) over great distances or over long periods of time?

Isn't the air pressure at sea level much more than it is on top of Mt. Everest, 8848 meters above sea level? This is because the column of air above the sea is nearly nine kilometers longer (higher) than the column of air above the mountain. So it weighs more. Similarly, the column of rock above

Figure 5.3 This schist (a metamorphic rock) contains garnets about 2 to 3 centimeters in diameter. The garnets formed in the rock during metamorphism.

a point deep below the surface of the Earth is long. The weight of this rock column causes high pressures. At a depth of 8 kilometers, the pressure is about 2400 atmospheres. At a depth of 40 kilometers, the pressure is about 12,000 atmospheres.

Besides this normal pressure due to the weight of overlying rock, other even stronger pressures (and unusually high temperatures) have occurred from time to time and have severely bent and fractured the rocks. This occurs in regions of mountain building, where rocks are squeezed and folded and broken over hundreds or even thousands of square kilometers. Rocks in such an area are generally metamorphosed. Because the area involved is so large, this type of metamorphism is called **regional metamorphism** (Figure 5.2). Metamorphism also occurs next to intrusions of magma. The heat of the magma and solutions from the magma change the adjacent rocks. This is called **contact metamorphism.** Zones of contact metamorphism are generally narrow, but if the magma body is large, the zone around it can be a few kilometers wide.

Is it any wonder, then, that rocks such as limestone and mudstone, which formed at the surface, change when they are deeply buried or come in contact with hot magma? But let's not make the mistake of assuming that all metamorphism occurs at higher temperatures and at higher pressures than those at which the minerals formed. For example, biotite in

igneous rocks crystallized out of hot magma. It can change to the mineral chlorite, a green mica, when exposed to temperatures of only a few hundred degrees.

During metamorphism, the temperatures may reach about 600°C, not hot enough to melt the rocks. (If they did melt, would we still be speaking about metamorphic rocks?) But the ions do move around *in solid rock,* especially when water is present to make their travels easier. Sometimes the ions present in the original rock simply rearrange themselves into new minerals. In other cases, ions are either added to the rock or taken away from the rock, usually with the aid of water.

Metamorphic minerals. Many minerals are found only in metamorphic rocks. Among them are asbestos, talc, staurolite, and kyanite. And some, such as garnet (Figure 5.3) are usually in metamorphic rocks. But the most important minerals in metamorphic rocks are the same common igneous rock-forming minerals you have already learned about. (1)

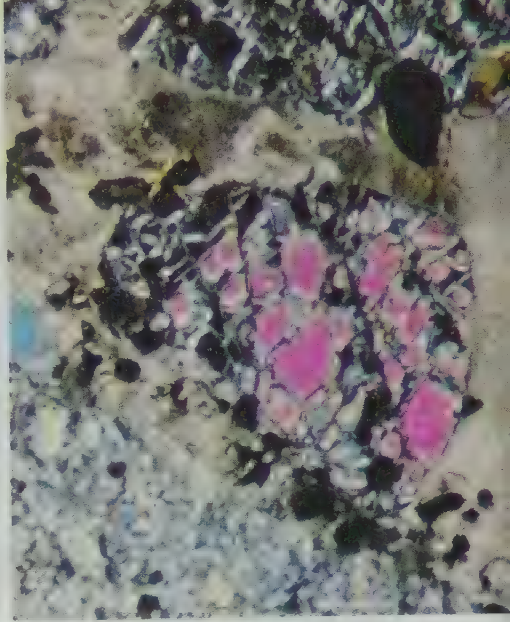


Figure 5.4 A mineral grain can be seen in the middle of this microscopic view of a metamorphic rock. The minerals that appear black and grey were formed during metamorphism from the mineral that appears purple.

(1) Another point worth emphasizing: In both igneous and metamorphic rocks, the volumetrically important minerals—quartz, feldspars, micas, amphiboles, pyroxenes, and olivine—are the same. (Olivine is the least abundant of these minerals in metamorphic rocks.)

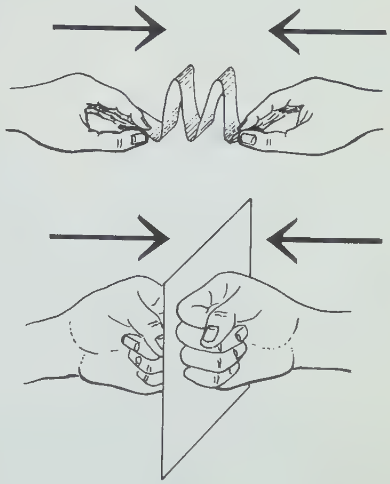
Clues to metamorphic history. About the turn of the century, geologists were realizing that minerals provide clues to the investigation of metamorphism. These geologists were the detectives in a hard-to-solve detective story. For example, in Scotland unmetamorphosed shaley rocks were traced through a series of gradual changes into highly metamorphosed rocks. Presumably these changes were due to progressively higher temperatures (and perhaps pressures) that occurred across the area during metamorphism. New minerals appeared in the metamorphosed shales and old ones disappeared. Shales, as you know, are made of clay minerals. In the slightly metamorphosed shales, chlorite appeared; and toward the more metamorphosed part of the area, biotite, staurolite, garnet, kyanite, and sillimanite appeared in that order. Studies elsewhere in the world showed that this sequence was common in other metamorphosed shales. How could this case be interpreted?

You already know that a given mineral is stable only under certain conditions of temperature and pressure. At other temperatures and pressures, the mineral will change to new minerals that are "happier" under the new conditions of the new environment. Sometimes an old mineral will be caught in the act of changing to a new mineral, so grains may be found that are partly one mineral and partly another mineral

(Figure 5.4). Such observations give geologists clues and ideas for laboratory experiments.

Geologists sometimes put various chemical compounds, minerals, or rocks into special containers in which the temperature and pressure can be controlled and varied. Then, by comparing their results with the observations made on rocks in the field, they may be able to solve the case. That is, they are able to figure out the temperature and pressure conditions of metamorphism. But, as we said in Chapter 3, geologists are always faced with that big bugaboo: They cannot reproduce the time spans of nature. For example, they may have run a laboratory experiment over a period of a month. Let's assume nothing happened. But would the old mineral have changed to a new mineral if the experiment had been continued for a million years? Maybe yes, maybe no. Change can take much time.

Figure 5.5 A sheet of paper, if pushed together from the ends, crumples up. But if pressure is applied from the sides of the sheet of paper, it doesn't crumple. The position is stable. Flat minerals such as mica grow in the stable position, at right angles to the pressure.



Textural changes. Thus far we have discussed only changes in mineralogy. Metamorphic rocks, like igneous and sedimentary rocks, commonly have distinctive textures, too. The minerals are commonly arranged so that they are parallel to one another and occur in layers or bands. This happens because the pressures are usually stronger in certain directions. These rocks are said to be **foliated**. New minerals that are long and narrow, or flat, grow so that their long directions are perpendicular to the strongest pressure (Figure 5.5). Similarly, existing minerals recrystallize or change positions so they are also in a stable physical position. Even pebbles in conglomerates recrystallize (Figure 5.6). In both the

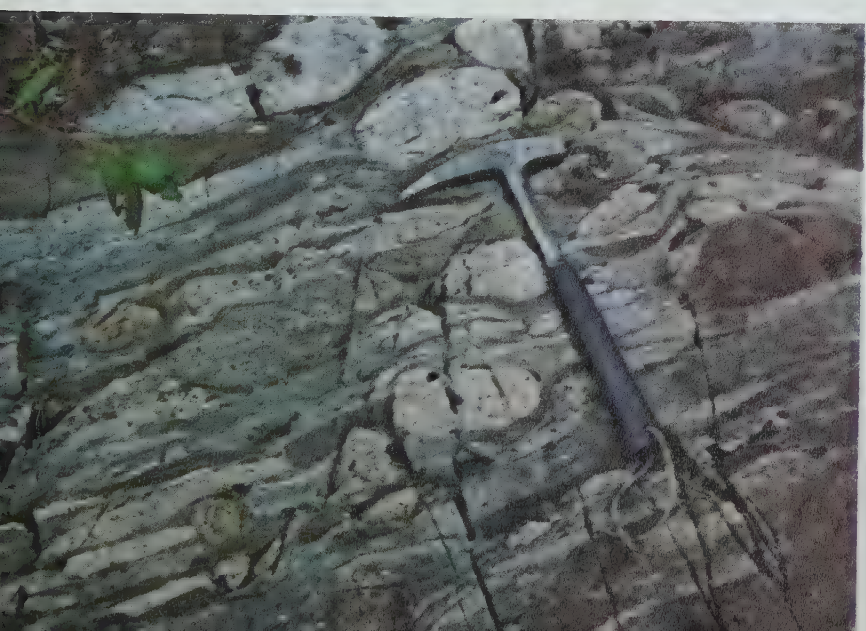


Figure 5.6 This conglomerate has been deformed by high temperatures and pressures. Most of the pebbles have recrystallized or have been "stretched," but the rounded granite pebbles have survived pretty well. Notice the layering or foliation through the rock.

growth of new minerals and in the recrystallization of old minerals, it is a matter of the ions choosing positions on the crystal structures where the pressure is the lowest.

If the metamorphosed rock was originally layered, the layering might be preserved after metamorphism. But layering can also develop in rocks that were originally massive, and it can even develop across the original layers. For example, in a thick bed of mudstone, the clay minerals will change to micas that are all parallel to each other. Slate is the result (Figure 5.7). Or a granite with no banding can become banded. However, if pressures are not stronger in one direction, the metamorphic rock will not be banded and the metamorphic minerals will not be parallel to each other. Figure 5.8 shows some microscopic views of metamorphic rocks and the original rocks that were metamorphosed.

Granitization. "Not all granites are igneous rocks!" some geologists say. And maybe you say: "But a coarse-grained igneous rock must have cooled from a magma!"

But careful mapping of some granites has shown that some sedimentary or volcanic rocks around the granites can

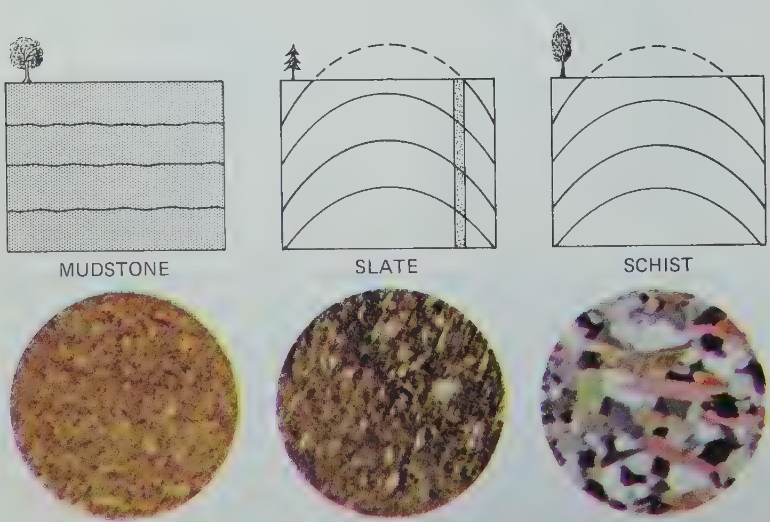


Figure 5.7 Metamorphism of mudstone to slate to schist is shown from left to right. The clayey mudstone beds are folded by pressure and metamorphosed to slate. In the slate, microscopic flakes of mica (light colored, visible in the microscopic view) have grown at right angles to the direction of pressure. The slate breaks into pieces parallel to the mica flakes, *across* the original beds. (The dark vertical band in the slate drawing represents pieces of slate.) In schist, increased temperatures and pressures have caused the mica flakes, as well as grains of other minerals, to grow so large that they can be seen without a microscope.

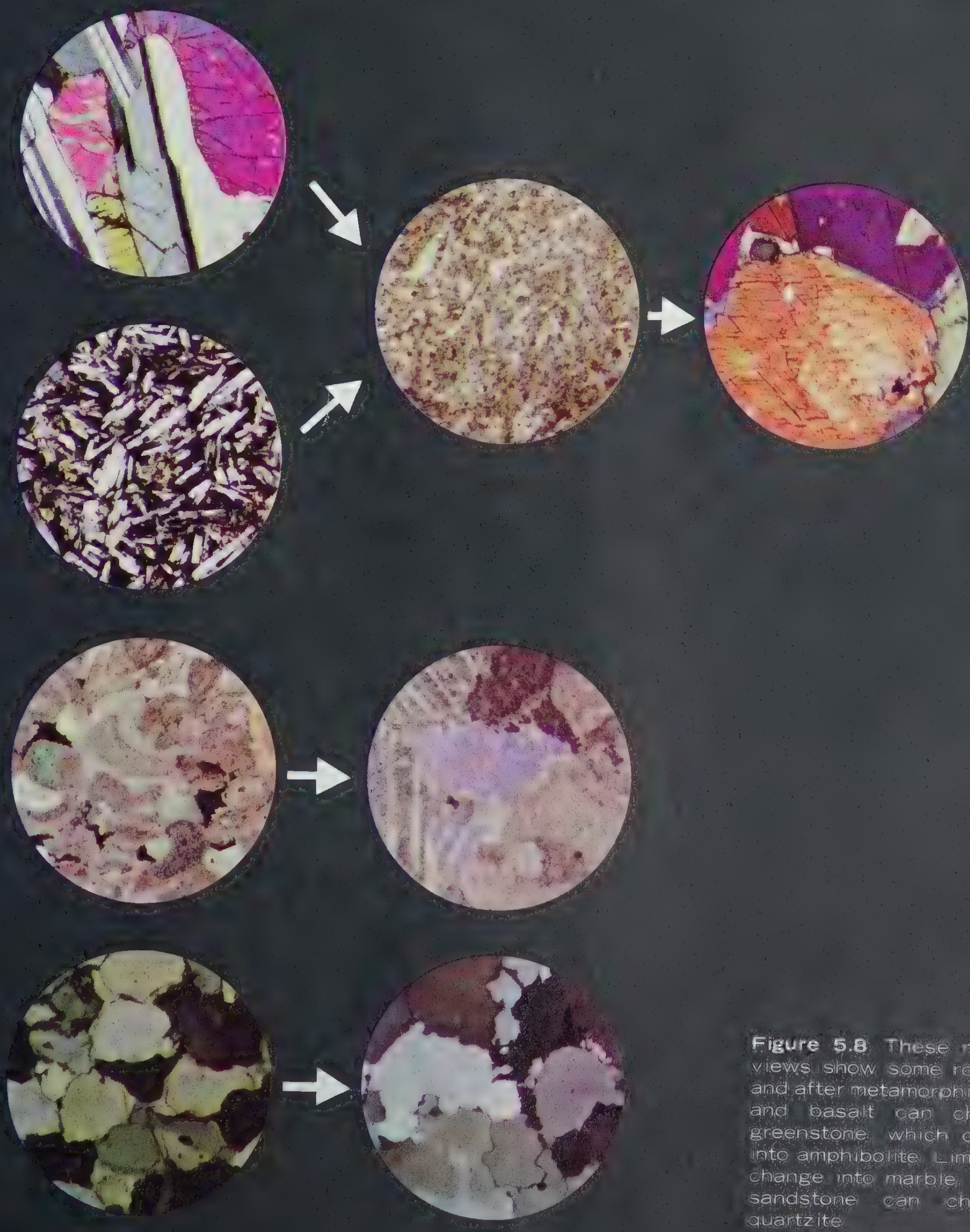


Figure 5.8 These microscopic views show some rocks before and after metamorphism. Gabbro and basalt can change into greenstone, which can change into amphibolite. Limestone can change into marble, and quartz sandstone can change into quartzite.

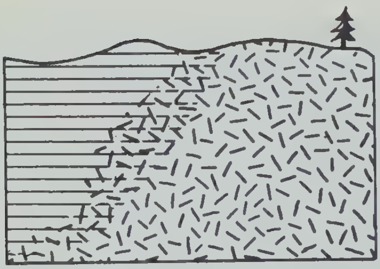


Figure 5.9 Granitization? Some layers of country rock can be traced into granite, without sharp boundaries.

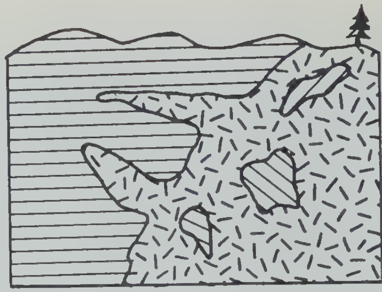


Figure 5.10 Magmatism? The boundary between the country rock and the granite is sharp. Note the inclusions.

be traced right into the granites. They become less and less distinct (Figure 5.9). Such evidence is hard to explain in any way other than to say that the country rock (the original rock) was changed to granite by solutions moving through the rock. This process is called **granitization.** This does *not* mean that the rock was melted. The fuzzy boundaries between the granites and the country rocks support this idea. And it gets rid of the "room problem" that geologists have a hard time solving: That is, where is the rock that used to be where the granite now is? Can magma push the country rocks apart and make room for itself? Or must it "eat up" the country rock?

(1)(1) Granitization is, of course, a special case of metamorphism.

Some granites have sharp contacts with other rocks, and are finer-grained near the edges, showing that they cooled more quickly there. These granites commonly contain pieces or inclusions of the country rock in various positions, indicating that they were moved about before the granite crystallized (Figure 5.10). These granites surely formed from magmas. And if the temperatures of metamorphism become too high, partial or total melting of the rocks will occur.

CHECK YOUR FACTS

1. At what rate does temperature increase with depth in Earth's crust?
2. What are the most important metamorphic minerals?
3. What is a typical arrangement of the mineral grains in metamorphic rocks?
4. Have all granites crystallized from magmas?

(2)(2) ANSWERS / Check Your Facts

1. On the average, 1°C for every 30 m of depth.
2. Quartz, feldspars, micas, amphiboles, pyroxenes, and olivine.
3. They are foliated (in layers or bands).
4. No.

METAMORPHIC MINERAL RESOURCES

Metals and minerals. Some mineral deposits were formed only by metamorphic processes. Asbestos, used as a fireproof material, is always a metamorphic mineral (Figure 5.11). It forms from the metamorphism of igneous rocks very rich in iron and magnesium. Talc, used in talcum powder, forms from the metamorphism of magnesium-rich sedimentary and igneous rocks. Large garnets, used for abrasives, also have a metamorphic origin.

During metamorphism, high temperatures and pressures and hot waters commonly cause valuable metallic ions to move around. A pile of volcanic rocks, for example, may contain only traces of copper, lead, zinc, and silver. But these ions may become very active under metamorphic conditions. They may move to spots of lesser pressures and be concentrated there in sufficient quantities to form valuable ore deposits. (Many of the metal mines of Canada may have had such a history.)

Figure 5.11 Suits made out of asbestos protect these fire fighters.

For this reason, areas of metamorphosed volcanic rocks are prospected very thoroughly. The ore deposits, however, may look much like those that many geologists think may have been deposited from the last solutions of a magma. Even though the origin of an ore deposit is often in doubt, geologists at least try to figure it out so they can use the evidence they have collected to help them find other, similar deposits. You don't have to completely understand something to get some good out of it!

Anthracite. A desirable kind of coal is called **anthracite**. It results from the metamorphism of lower-grade coal. Much of the moisture and gases have been driven off, leaving a coal richer in carbon. Intense metamorphism drives out all the gases, leaving the mineral graphite, which will not burn, but is valuable as a dry lubricant because it breaks into flat, slippery flakes. The "lead" in your pencil is graphite mixed with clay, not the element lead. And you have already read about the artificial metamorphism of graphite to produce diamonds.

(1)(1) We haven't gone into the different types of coal. This might make a good topic for student reports.

Building Stones. **Marble**, which is metamorphosed limestone, is much used as a building stone. The best grades are also used for sculpturing; the softness of calcite makes it easy to work with. **Slate**, which is metamorphosed shale or mudstone, used to be quarried for blackboards, but now blackboards are made of artificial materials. Most slate is now used for stones for roofs. It comes naturally in different colors —gray, blue-black, red, green, and purple.

CHECK YOUR FACTS

1. What are some important metamorphic mineral resources?
2. How do metamorphic processes concentrate metals?
3. How is anthracite formed?

(2)(2) **ANSWERS** / Check Your Facts

1. Asbestos, talc, and garnets.
2. Because metal ions were moved in hot solution to places of lesser pressure and concentrated there.
3. By metamorphism.

APPLYING WHAT YOU HAVE LEARNED

1. Geologists think that many metamorphic rocks formed at depth under high temperatures and high pressures. How can they tell, since they obviously can't get down there to see what happens under these conditions?

(3)(3) **ANSWERS** / Applying What You Have Learned

1. By combining field evidence (made available by uplift and erosion of the rocks from depth) and data from laboratory experiments.

2. In Chapter 2 you learned that cleavage in minerals is the result of the internal arrangement of the ions. In mica, the ions are arranged in sheets, and because of this, micas have an excellent cleavage. The same word, cleavage, is used to describe the manner in which slate breaks into flat pieces (see Figure 5.7.). Is this "slatey cleavage" also due to the internal arrangements of ions in the slate?

3. How could the presence or absence of contact metamorphism next to layers of igneous rock interbedded with sedimentary rocks help tell whether the igneous rock was once a lava flow on the surface or a layer of intrusive rock formed by magma squeezing in between the layers of sedimentary rock?

4. Near some small intrusions, there is little evidence of contact metamorphism. What conditions at the time of intrusion might be responsible for this?

2. Yes, slaty cleavage in rocks is also due to the arrangement of ions in the mica grains. However, this cleavage is different from mineral cleavage in that the slate generally breaks along the flat sides of mica grains or crystals, rather than along the planes of ions in the mica crystals. The same is true in schists—they break along the flat sides of mica crystals.

3. A lava flow could metamorphose only the rock immediately beneath it because there are no rocks above a flow when it forms. An intrusive layer (the sill of Figure 6.17) would metamorphose the rocks immediately above as well as those immediately below.

4. Probably the small intrusion didn't have enough heat and fluids to alter the country rocks.

KEY WORDS

metamorphism (p. 89)
regional metamorphism (p. 91)
contact metamorphism (p. 91)
foliated (p. 93)
granitization (p. 96)
anthracite (p. 98)
marble (p. 98)
slate (p. 98)

Figure 6.1 Kilauea volcano, on the 'island of Hawaii, is shown during an eruption.

Introductory Demonstration

Show one of two excellent films: "Volcano," showing the birth of Paricutin (CUE), or "Volcanic Violence" showing eruptions in Hawaii (FILMS).

chapter 6

Volcanoes, Earthquakes, and Earth's Interior

Our old Earth may seem to be quiet, stable, and well adjusted. But it isn't. Often it blows up and lets off steam through volcanoes, and many times a day its inner tensions cause earthquakes somewhere on its surface. But most of us don't see volcanoes or feel earthquakes. That's because most of us don't live in areas where Earth's crust is weak; those are the areas where volcanoes and earthquakes occur most often.

Tremendous amounts of energy are released by volcanoes and earthquakes. A volcano on the island of Krakatoa in the East Indies exploded in 1883. The explosion was heard 5000 kilometers away. An earthquake in Missouri in 1811 was felt over an area of $2\frac{1}{2}$ million square kilometers. The vibrations even rang bells in Boston, more than 1600 kilometers away.

VOLCANOES

Volcanoes are probably the most spectacular of nature's activities. Man has long feared death and destruction by volcanoes. To try to make living a little safer, the Romans worshipped the volcano god, Vulcan. Yet some of the most populated areas on Earth are in areas of active volcanism. Why doesn't man just move away? One reason is that volcanic material in many of these areas is quickly weathered to a rich soil. So Vulcan can't be all bad, can he?

Paricutín. One day in 1943, a Mexican farmer was tilling his cornfield with his wife. Bad-smelling steam started rising out of a small hole in the field. He kicked rocks into the hole, as he had done many times in the past year. Then he kicked in some dirt and stamped it down. But the hole wouldn't stay shut. It got bigger and bigger. More and more steam was coming out and the earth was starting to rumble. Finally the farmer became alarmed. But he kept his wits about him. He left his wife to watch the hole and he ran into town for help. (After he took off, so did she).

By the next day there was a hill of cinders ten meters high. A new volcano had been born. The people named it Paricutín, after the nearby town. But the new baby wasn't loved. Everyone, except geologists, hated it. Geologists flocked to witness the birth of Paricutín. It became a terrific field laboratory for volcanologists. And the baby grew. In five days

Figure 6.2 San Juan was buried by basalt flows from Paricutín, which can be seen in the distance.

Figure 6.3 A "fiery cloud" roars down Mt. Pelée.

it was 100 meters tall. Day and night it threw out red-hot hunks of material. In a year it was 430 meters high. Eventually basalt flows poured out of cracks near the base of this cone-shaped volcano and covered the town of San Juan (Figure 6.2). By the time Paricutín was six years old, it was over 600 meters high. Not until nine years after its birth did it become quiet. Paricutín is probably dead now, but we can't be absolutely sure.

Mt. Pelée. On the island of Martinique, in the West Indies of the Caribbean, a different kind of event occurred in 1902. On April 23, after 50 years of no activity, Mt. Pelée, the island's volcano, began to erupt. Animals sensed the danger and left the mountain. Birds stopped singing on its 1350-meter-high slopes. Ash and fumes from the volcano gave many of the people on the island sore throats and sore eyes. People started to worry. Schools closed. On May 5, muddy ash rushed down the slope and covered a sugar mill. Only the smoke stack could be seen. Forty men were buried alive.

Mt. Pelée is eight kilometers from the seaside city of St. Pierre, which was "the Paris of the West Indies," the pride of Martinique. When Mt. Pelée started to act up, three hundred people left St. Pierre each day, but each day a thousand frightened farmers flocked in from the countryside.

On May 7, another eruption. Some said the city should be evacuated, but May 10 was election day. The local newspaper tried to calm the peoples' fears and urged them to stay and vote.

A ship captain who had seen the volcano Mt. Vesuvius in action in Italy was loading his ship with sugar at St. Pierre. He left, even though his ship was only half loaded.

At 7:59 on the bright morning of May 8, in a blinding flash, the top of Mt. Pelée vanished! A great "fiery cloud" of (1) red-hot volcanic ash and gas roared down the mountain at a terrific speed (Figure 6.3). At 8:02, the city clock stopped forever. The city burned. Burning rum from exploded rum barrels poured down the streets into the harbor and set ships on fire. And in those three minutes, the fiery oxygen-poor cloud did in the entire population of 30,000 people . . . well, almost the entire population. Two persons lived. One was a shoemaker who miraculously lived although people all around him died. The other was a man in jail for murder. His underground cell, with only a small window, saved his life. (He was found four days later, burned and barely alive. Doesn't it seem only right that he was pardoned and made a free man?) (2) A real happening happened at St. Pierre that day!

(1) Other "fiery clouds," over 100 of them, rushed down Pelée's slopes in 1929, but missed the city. (These clouds are known as *nuées ardentes*, but your students don't need this term—*fiery cloud* is better.)

(2) Epilogue: The night after the jailed man was freed, he was supposed to have returned to his cell to sleep, because he could find no other bed!

Figure 6.4 Crater Lake.

Crater Lake. Crater Lake, Oregon (Figure 6.4) has also had a spectacular history. It was once a nice symmetrical volcano, but now it is a deep, broad crater. By projecting imaginary lines from the walls of the crater upward to a peak, the original size of the volcano can be determined. There is little doubt that it was once 3500 to 4500 meters high. Today the lake is 1850 meters above sea level. What gives? Or, what gave?

This missing ancient volcano has been named Mt. Mazama. At first, geologists thought that Mt. Mazama had blown its top off, like Mt. Pelée. This idea was supported by the finding of small broken pieces of volcanic rock for miles around the volcano. But closer study of the pieces showed that most were glassy ash and cinders. These must have been blown from the volcano during normal eruptions. There just weren't nearly enough pieces of actual volcanic rock with which to "reconstruct" the original large volcano. So geologists concluded that Mt. Mazama didn't blow apart. Instead, it must have collapsed back into its own magma chamber. Wouldn't the chamber have been partly empty after all the explosive volcanism?

The dating of trees killed by the last ash fall at Crater Lake indicates that the violent end of Mt. Mazama occurred about 6600 years ago. Perhaps some Indians saw it happen? Wizard Island, the small island cone in the large crater, is obviously much younger.

Mt. Mazama was one of many volcanic peaks in the Cascade Range (Figure 6.5). (The other volcanoes did not collapse.) They are found along a zone 800 kilometers long and 80 kilometers wide, about 150 kilometers inland from the Pacific Coast. There are hundreds of small volcanoes, but we only hear about the big ones. Nine of the peaks are over 3000 meters high. The Cascades are especially interesting because, geologically speaking, they are very young. Erosion has hardly changed the nice symmetrical cones. The most recent volcanism in the continental United States was in this zone. Mt. Shasta erupted ash in 1786. Not to be outdone, Mt. St. Helens erupted several times between 1831 and 1854. Mt. Baker was active about the same time. Mt. Lassen laughed last, erupting in 1914 to 1917; in one year it erupted more than 100 times. Mt. Rainier still steams a little in its snowy crater, an exciting sight for the many tourists who climb up it. (Do you think they are done erupting, or just "resting"? No one knows, but if they blow, we'll surely know!)

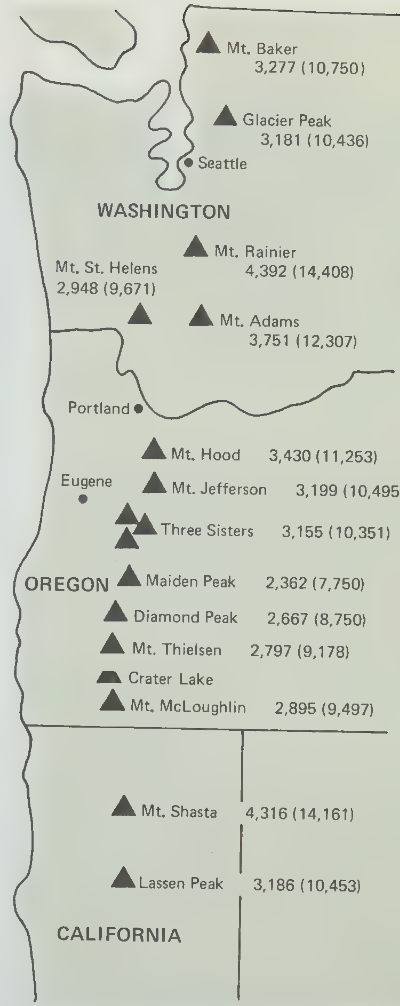


Figure 6.5 The Cascade Range. Elevations of the peaks are given in meters, then in feet.

Figure 6.6 Ship Rock.

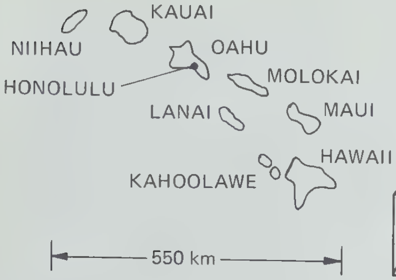


Figure 6.7 Part of the Hawaiian Islands chain.

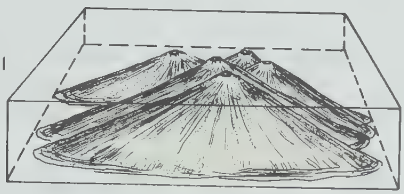


Figure 6.8 The volcanoes that form Hawaii Island rise from water 5000 meters deep.

The ash deposits around many of these cones, including Crater Lake, include some ash deposited by "fiery clouds." Mt. Pelée isn't alone.

Ship Rock. Mt. Mazama disappeared quickly and violently. Other volcanoes have faded away slowly. Ship Rock, in the Navajo Reservation of northwestern Mexico, is the remains of lava that plugged the throat of an ancient volcano (Figure 6.6). Erosion by running water and wind over a long period of time has removed the softer ash that made up most of the volcano. Only the harder parts remain.

Hawaii. A group of volcanic peaks sticks out of the Pacific Ocean, forming a chain of islands 2500 kilometers long. These are the Hawaiian Islands (Figure 6.7), and the largest of them is Hawaii. Hawaii is really five volcanoes (Figure 6.8) grown together. At least two of the volcanoes are still active.

Mauna Loa, one of the five volcanoes on Hawaii, is nearly 150 kilometers across. Its top is about 4264 meters above sea level. The sea around the island is about 5000 meters deep. Thus, Mauna Loa rises more than 9200 meters above the sea floor and is a higher mountain than Mt. Everest! But Mt. Everest, at 8848 meters above sea level, is still the highest mountain on land.

The Hawaiian volcanoes are made of basalt. The eruptions of basaltic lava are quiet, compared to the other volcanic activities we have studied. However, blobs of red-hot liquid basalt are often thrown over 100 meters into the air, creating spectacular fireworks at night. Hawaii is the site of one of the world's best centers for the study of volcanoes.

Types of volcanoes. There are three main types of volcanoes. Most small volcanoes are made up nearly entirely of **pyroclastic** (fire-broken) **particles** thrown out of vents. These volcanoes are called **cinder cones** because the glassy, rapidly-cooled particles look like cinders and ash. Cinder cones are the smallest and most abundant kind of volcano (Figure 6.9). The main cone of Paricutín is a fine example of a cinder cone.

The large symmetrical cones that you probably think of when you hear the word "volcano" are **composite cones** (Figure 6.10). They are made up of alternating pyroclastic layers

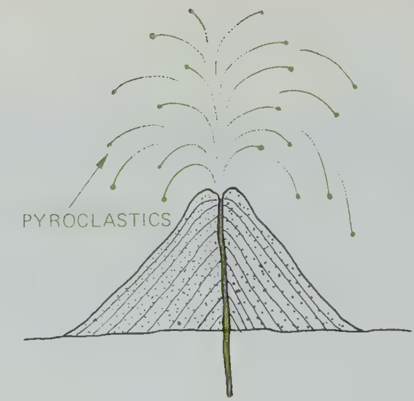
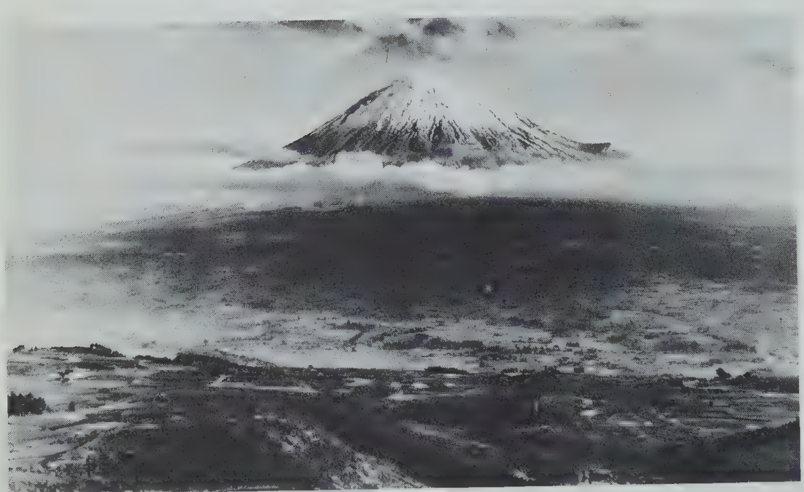


Figure 6.9 Cinder cones are made of pyroclastic particles.



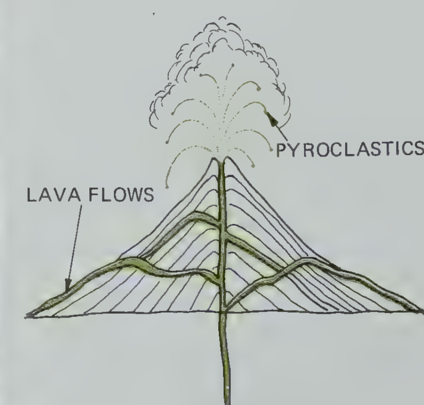


Figure 6.10 Composite cones are made of pyroclastic layers and lava flows. The photograph shows Mt. Fuji, a composite cone in Japan.

and lava flows. The lava is somewhat sticky and does not flow very far. The most spectacular volcanic cones in the world are composite cones. Mt. Mazama was a composite cone, as are the peaks in the Cascades.

Shield volcanoes are broad, low volcanoes with no impressive cones at all. They resemble round, flat shields lying on the ground (Figure 6.11). They are made of basaltic lava flows that were very hot and "runny." The lava quickly flows away from the craters and doesn't build steep cones. These volcanoes are relatively quiet compared to the other types, but they are the largest volcanoes. The Hawaiian volcanoes are shield volcanoes.

Where are volcanoes? At last count, there were about 500 active volcanoes in the world. An **active volcano** is one that has acted up within the last 50 years or so. Some volcanoes haven't erupted in that time, but are probably just sleeping. They are called **dormant volcanoes**. **Extinct volcanoes** are volcanoes that haven't erupted, as well as man can tell, in recorded history. But extinct volcanoes may just be very sound sleepers. They might wake up any time.

In the geologic past, volcanoes existed in many parts of the world, but the active ones today are concentrated in two main belts (Figure 6.12). One, called the "Ring of Fire," circles the Pacific Ocean. The other runs east and west from the Atlantic Ocean through the Mediterranean Sea and across Asia.

Most of the remaining volcanoes are in the ocean basins; many of these are on elevated zones called ridges. The Mid-Atlantic Ridge, which runs right through Iceland, is particularly active. A volcano appeared on the Mid-Atlantic Ridge

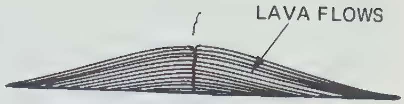
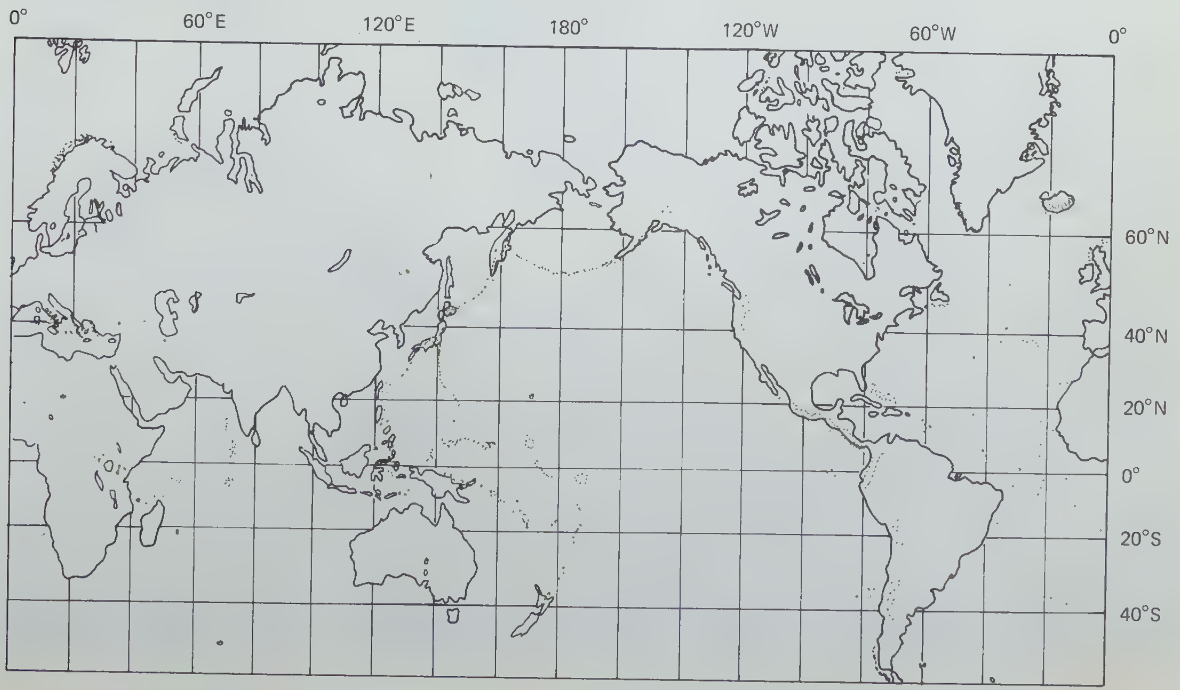


Figure 6.11 Shield volcanoes are made of basaltic lava flows. **(1)**

(1) In Figure 6.11, all layers should be lava flows. There are few layers of pyroclastics in classic shield volcanoes.

Figure 6.12 Active volcanoes (colored dots) are found today in a ring around the Pacific, in a belt that runs through the Mediterranean Sea (left) and Asia, and in the oceans.



near Iceland in 1963. From a depth of 120 meters, it rose above the surface in a spectacular display. The island was named Surtsey (Figure 6.13) after the giant Surtur, who in Norse mythology fought another god with fire just before the world ended.

Basalt floods. In the Columbia River area of the northwestern United States, there is a thick pile of basaltic lava flows (Figure 6.14). Most of the individual flows are 3 to 5 meters thick, but in many places they total more than 1500 meters, and at some places they are more than 4 kilometers thick. They cover more than 550,000 square kilometers (Figure 6.15). The total volume of volcanic rock in this area has been estimated at 400,000 cubic kilometers. Surely this must have been one of the greatest outpourings of lava that has ever occurred in the world. Geologists figure it happened 10 to 25 million years ago.

Figure 6.13 Surtsey (shown in the back) rose explosively from the Atlantic in 1963. The island shown in front rose later, but has since been completely worn away by wave action.

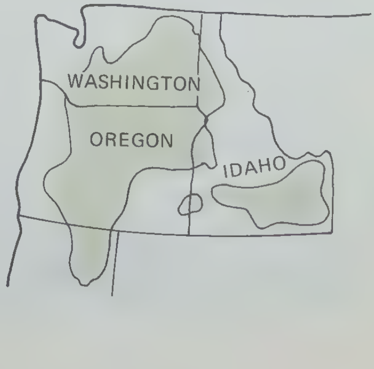
Figure 6.14 How many lava flows can you see in this cliff?

There is a similar but much older pile in India. Still another thick volcanic pile exists in the North Atlantic; remains of it can be found in Ireland, Scotland, Greenland, and Iceland. And on the shores of Lake Superior there are remains of a billion-year-old volcanic pile. Could such great piles of hardened lava flows come out of single volcanoes? That doesn't (1) seem possible, does it?

(1) You might have some students do research to determine and compare the areas of the Deccan Plateau in western India, the area of Lake Superior (with a few extra miles on each side), and the area in the North Atlantic with that of the Columbia Plateau.

If we apply the principle of "the present is the key to the past" once again, we can see how it happened. In 1783 at Laki, Iceland, a flood of basalt poured out of a 32-kilometer-long crack in the earth and covered an area of 560 square kilometers. Twenty percent of Iceland's population of 50,000 people and much of the livestock were killed.

Figure 6.15 Areas covered by lava flows are shown in color.



It appears that the ancient thick piles of basalts were formed in the same way. The lava must have poured out of great systems of cracks in order to cover such big areas. And doesn't it seem that the lava must have been very runny? Some flows on the Columbia Plateau can be traced for more than 150 kilometers. **Basalt floods** is a good name for this type of volcanic activity, don't you think?

Yellowstone National Park is located on a rhyolite plateau that is about the same age as the Columbia Plateau. Probably

the most interesting features in the park are the hot springs and geysers (Figure 6.16). It has a complex volcanic history. Rainwater and water from melting snow flows down cracks in the volcanic rocks. The water gets heated by hot rock at depth. The steam that forms drives the hot water upward, causing a kind of an eruption. In Yellowstone, there are 200 geysers and 3000 hot springs. There must be a lot of plumbing down there someplace.

Figure 6.16 Old Faithful geyser in Yellowstone National Park "erupts" about once every hour for about five minutes. Each time it throws out about 40,000 liters of water.

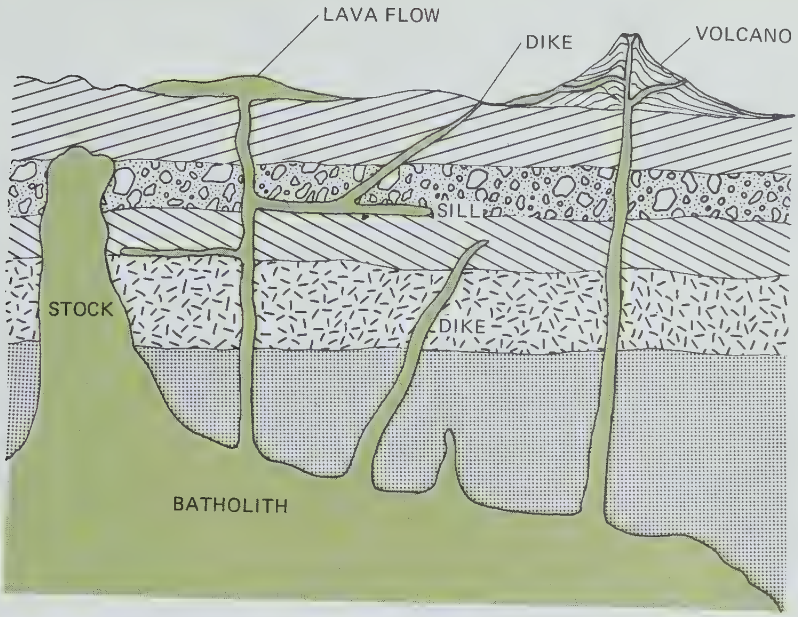


Figure 6.17 Various igneous rock bodies are shown in color.

Plutonic rock bodies. As you learned in Chapter 3, much magma never reaches the surface. It cools slowly, as the rocks around the magma keep the heat in. These coarse-grained bodies of rock come in many different sizes and shapes (Figure 6.17). The largest intrusions are **batholiths**, which generally form in the cores of mountain ranges. The Sierra Nevada batholith in California is more than 600 kilometers long and as much as 100 kilometers wide. **Dikes** and **sills** are (1) smaller offshoots. If these bodies of plutonic rock formed underground, how can we see them today? (As you undoubtedly just said to yourself, they must have been exposed by erosion.)

(1) Sills are intruded parallel to the layers in the country rock. Dikes cut across the layers. [You might draw some vertical beds and then draw in a sill parallel to them and ask your students whether it's a dike (incorrect) or a sill.] Technically, a batholith has an area of more than 40 square miles, and a stock has an area of less than 40 square miles. But the numbers are unimportant—batholiths are the big ones. Other books may describe laccoliths (mushroom-shaped intrusions) and lopoliths (saucer-shaped intrusions), but they are uncommon, so why bother with them?

CHECK YOUR FACTS

(2)

1. What happened to the volcano that was located at Crater Lake?

2. What are the three types of volcanoes and how do they differ from one another?

3. In what general regions are most of the active volcanoes of the world located?

(2) **ANSWERS** / Check Your Facts

1. It probably collapsed back into its magma chamber.
2. Cinder cones, composite cones, and shield volcanoes. See page 109 for differences.
3. In a ring around the Pacific, a belt through the Mediterranean, and in the oceans.

EARTHQUAKES

Tremendous amounts of energy are involved in big earthquakes. If an earthquake occurs in a populated area, the death and destruction can be terrible. The 1906 earthquake in San Francisco killed 700 people. Many died in the fires that started due to breaks in gas lines (broken water lines didn't help, either). In Corinth, Greece, in 856 A.D., 45,000 people were killed. In western China, 100,000 were killed in 1920 and again (different people) in 1927. In 1923 in the Tokyo-Yokohama area of Japan, 142,809 were killed or missing and 103,733 were injured. It's quite likely, nearly certain, that during your lifetime a big earthquake will hit a heavily populated area in the world. Our Earth can be really wicked!

Alaskan "Good Friday" earthquake. The Good Friday 1964 earthquake in Alaska was one of the largest earthquakes ever recorded. It released energy about equal to the energy released in exploding $31\frac{1}{2}$ million tons of TNT. Tops of trees were snapped off near the earthquake center and land was raised and lowered a meter or so over 140,000 square kilometers. Half of Alaska shook quite noticeably. Swimming pools sloshed in Texas. The entire Earth vibrated slightly.

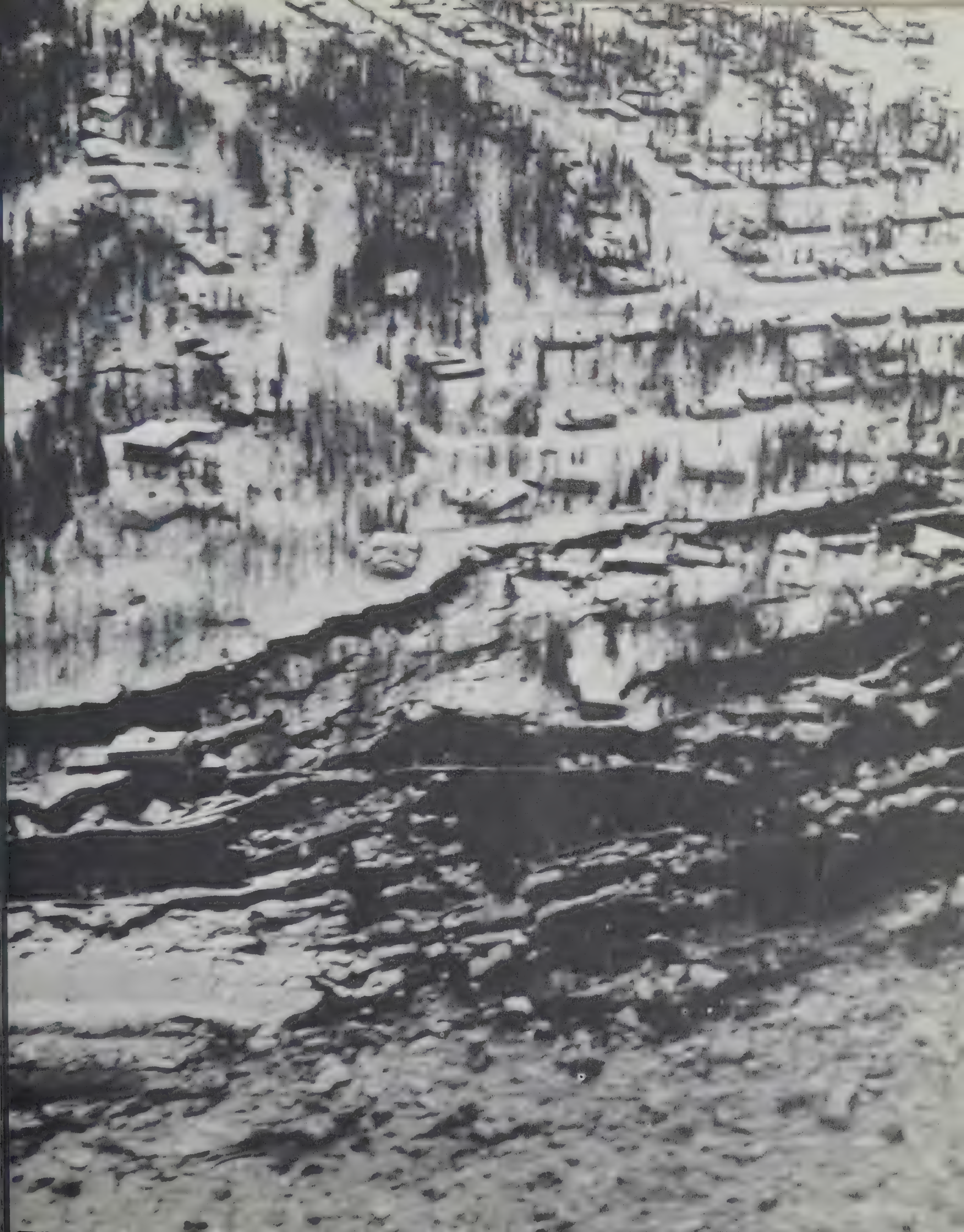
Fortunately, not many people live in Alaska. Only 114 people were killed; however, some people were even drowned in northern California, more than 2700 kilometers away, by a big sea wave caused by the earthquake.

Damage by this earthquake totaled $750,000,000. Most of the damage was due to landslides triggered by the earthquake (Figure 6.18). Geologists of the United States Geological Survey could have said, "We told you so." Five years earlier they warned people not to build on the clay slopes of Anchorage, predicting that future earthquakes could cause bad landslides. An ounce of prevention is worth a pound of cure, especially when we will probably never find the cure for earthquakes.

Where do earthquakes occur? Most earthquakes occur around the Pacific Ocean (Figure 6.19). Another zone of earthquakes runs from the Mediterranean through Turkey and Afghanistan and then through Asia. Others occur along the ridges in the oceans. Does all this sound familiar? (At least some brain cells should start vibrating!)

Probably no place on Earth is completely safe from earthquakes. An earthquake could occur anywhere, although over most of Earth's surface they are rare.

Figure 6.18 This landslide was triggered by the Good Friday 1964 earthquake in Alaska.



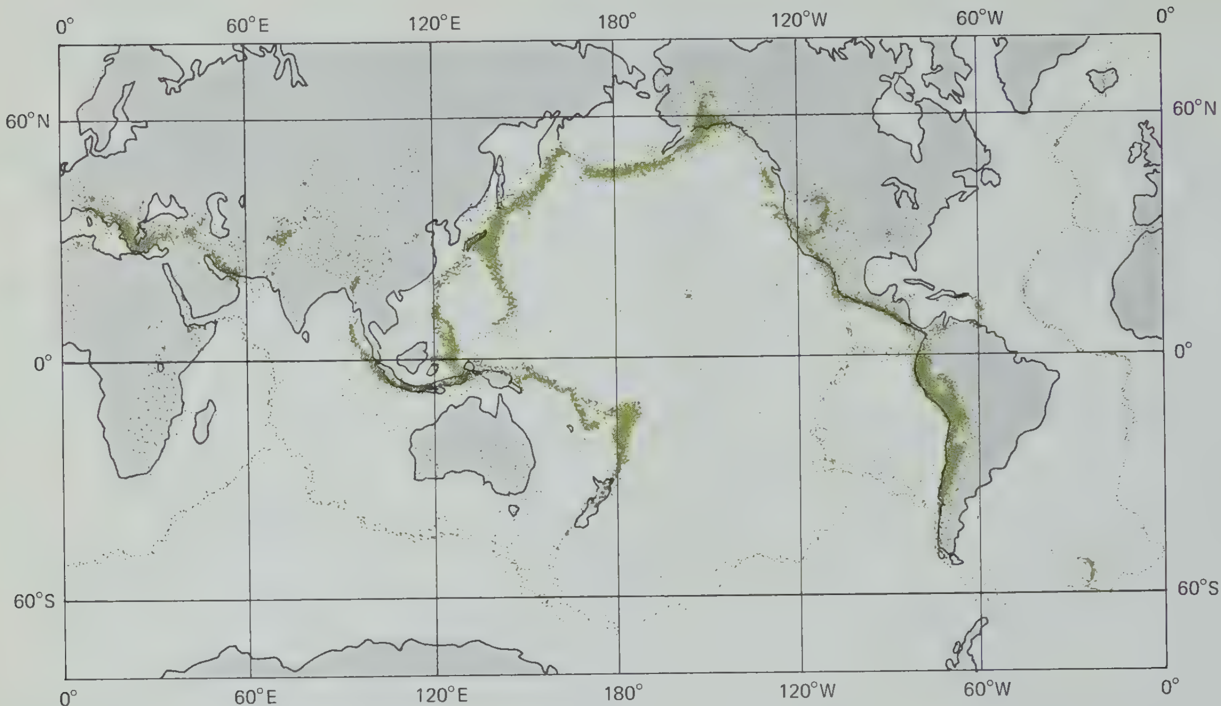


Figure 6.19 The locations of earthquakes are shown on this world map by colored dots.

Causes of earthquakes. Why does the Earth shake? The lamas of Mongolia thought Earth was resting on top of a giant frog. When the frog moved one of his feet, Earth quaked. (But we know this isn't true—our astronauts looking back at Earth from space didn't see any frog.) The movement of magma beneath volcanoes causes some earthquakes, and volcanic explosions cause others. But most earthquakes are not directly related to volcanic activity. As internal Earth pressures build up near a **fault**, (a crack in Earth's crust along which movement occurs), the rocks tend to move along the fault. Usually the friction of rock against rock in the fault is great enough to prevent movement, temporarily. But eventually the pressure becomes stronger than the friction. Suddenly there is movement and a great BANG! This sudden movement causes vibrations to move out into the rocks from the place of movement. The Earth shakes, or quakes. Most earthquakes are caused in this manner—by movement along faults. Most occur at depths of 8 to 32 kilometers, but some are as deep as 650 kilometers. The deep earthquakes tell us that the rock at that depth is still solid. (How do they tell us this?)

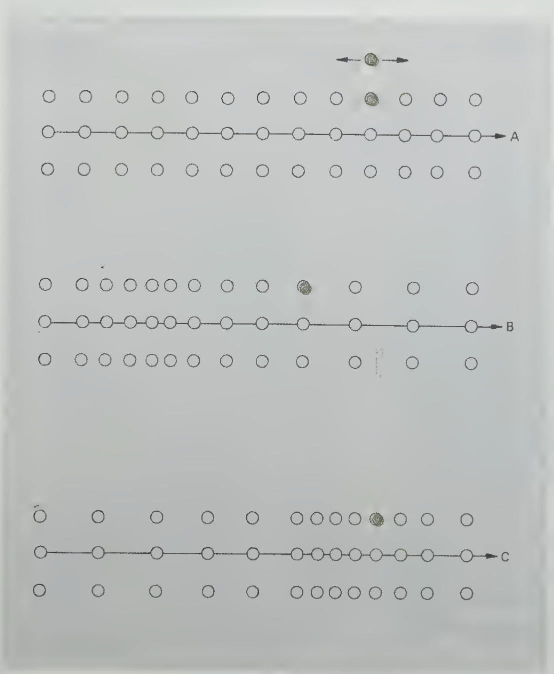
Detecting earthquakes. Three main types of waves or vibrations move out from the site of an earthquake. These are surface waves, P waves, and S waves. Surface waves are the ones that cause the damage. P and S waves are important in detecting and locating earthquakes. A **P wave** ("push-pull wave") is similar to a sound wave. When it moves through a material, the particles that make up the material are alternately squeezed together and pulled apart. Each particle vibrates back and forth, along the direction of the wave's travel (Figure 6.20). An **S wave** ("shake wave") is similar to the waves you produce if you shake one end of a rope with the other end tied to something. When an S wave moves through a material, the particles of the material vibrate sideways, at right angles to the direction of the wave's travel (Figure 6.21). A **surface wave** is more complicated than either P or S waves. It is slow, somewhat like a water wave, and travels on the surface of a material rather than through it. P waves can move through solids, liquids, and gases. S waves, which are slower, can move only through solids.

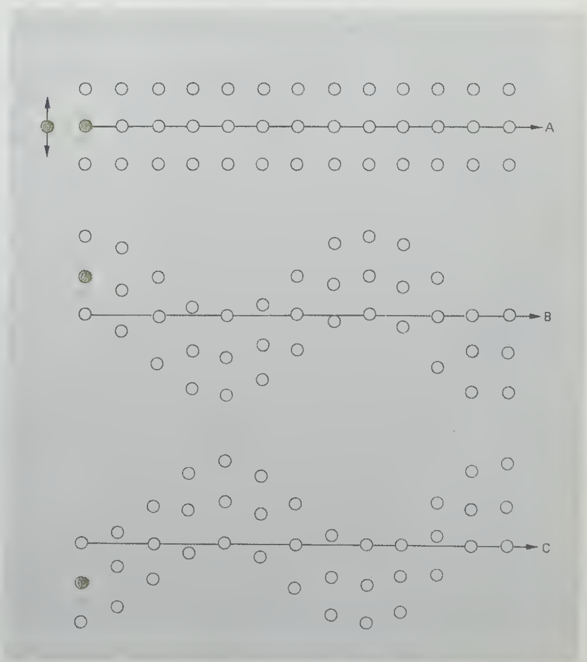
Earthquakes are measured or recorded on instruments called **seismographs** (Figure 6.22). A seismograph is built so that part of it is attached to solid rock and part of it isn't.

(1) Explaining P waves can be difficult. During the passage of a P wave, the rock material is alternately "compressed" and "stretched." During passage of an S wave, the rock material goes up and down. To illustrate the S wave, tie a rope to a chair or doorknob, color one short part (3 cm) of the rope red with chalk or paint, and shake the free end up and down.

Figure 6.20 (below left) In part A, the material is at rest. In parts B and C, a P wave is moving through the material from left to right. Movement of each particle is as shown by the colored dots.

Figure 6.21 (below right) An S wave is moving through the material in parts B and C. Particles move sideways rather than back and forth.





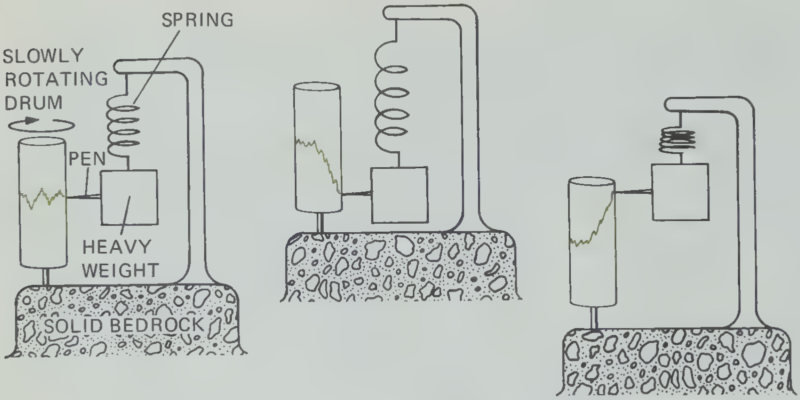


Figure 6.22 The heavy suspended weight records the movement of the rest of the seismograph.

When the Earth shakes, the part of the seismograph attached to solid rock shakes, too. The other part, a heavy suspended weight, moves very little. A pen or some other device records the relative movement between the two parts, and the resulting chart is called a **seismogram** (Figure 6.23).

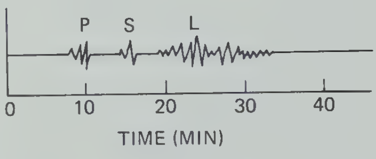


Figure 6.23 The arrival times of various waves are shown on this seismogram. L indicates surface waves.

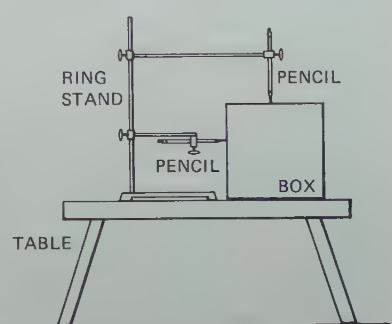
activity 6.1 Building a seismograph

You can build a crude seismograph that will illustrate how earthquake waves are recorded. You will need a ring stand with clamps, a cardboard box about 20 to 50 centimeters on a side, and paper. Set up the apparatus as in Figure 6.24. One pencil is held by the upper clamp in a vertical position, touching the box. The other pencil is held by the lower clamp in a horizontal position, also touching the box.

Compare this setup with a diagram of a real seismograph (Figure 6.22). In our simple model, imagine that the box represents the part of the seismograph attached to solid ground. When the box is shaken, its movements represent Earth movements. Imagine the pens to represent the suspended, unmoving part of the seismograph.

Insert a sheet of paper under each pencil. Have someone slowly pull the paper while someone else shakes the box. Note that the vertical pencil records only horizontal movements and that the horizontal pencil records only vertical movements.

Figure 6.24 A homemade model of a seismograph.



(We have really built two seismographs in one. Most seismographs record only one type of movement.)

Does our seismogram show both P and S waves?

Besides earthquakes, what other types of vibrations might be recorded on a sensitive seismograph?

(1) Our crude seismograph records only our "artificial" wave. (It is neither a P nor an S wave). Sensitive seismographs record passing trucks, explosions on construction projects, and similar things.

(1)

Seismologists (earthquake specialists) have figured out how fast earthquake waves travel. To find out how far away from the seismograph station an earthquake occurred, they simply note the difference in arrival times of the P and S waves at the station and then look at a table that looks like a kind of train schedule. For example, say that the S wave arrived 4 minutes and 52 seconds after the P wave. The table will tell them that the earthquake was 3200 kilometers away.

If an earthquake is recorded on three seismographs at three different places, it can be accurately located. The distance of the earthquake from each seismograph is plotted on a map. Each plot is a circle whose center is the seismograph station and whose radius is the distance of the earthquake from that station. The earthquake occurred at the point where the three circles cross each other (Figure 6.25).

Figure 6.25 An earthquake can be located if it is recorded at three different seismograph stations. Can it be located if it is recorded at two stations? At one station?

The strength of an earthquake is indicated by the strength of the vibrations. One scale of earthquake strength is based on the observations of people who were near the earthquake. Sometimes scientists send post cards to people in the area asking what happened there. Answers vary from "The pictures on the wall were swinging back and forth" to "I was knocked right out of bed onto the floor and I screamed." Then the investigators make a dot-to-dot map. They connect the points of "equal shake," or really, "equal fright." But earthquakes are probably much like fish. They grow every time that the story is told.

A more scientific method uses the vibrations recorded on the seismographs to estimate the energy of the quake. A scale of 1 to 10, called the **Richter scale,** is used. Earthquakes with Richter values of more than 7 are destructive. The two biggest earthquakes ever recorded had values of 8.6. One was in India, the other in Colombia. The scale is not an arithmetic scale. For example, an earthquake of magnitude 8 releases about 3,000,000 times more energy than one of magnitude 5. The first atomic bomb released energy of about magnitude 5, but of course the energy from an atomic bomb is very concentrated and does great damage.

Can we predict earthquakes? Detailed land surveys have been made along the San Andreas Fault, the famous California crack. It has been determined that the land west of the fault is moving north at the rate of 2 centimeters per year. To better concentrate on the fault, seismologists have even set up a laboratory in a winery at Hollister, on the fault. **(1)** This winery was built on a part of the fault that moved during the San Francisco earthquake of 1906. In fact, the new winery is built on the foundation of the old winery that was wrecked in 1906! The winery is literally being torn in half by movement along the fault. Several times wine barrels have broken because of earthquakes and thousands of gallons of wine have flowed away. Probably many local people grab empty buckets and jugs and head for the winery when they feel an earthquake.

(1) A cool spot for a laboratory!

But predicting earthquakes is difficult. We don't yet know enough about them. Do several small earthquakes mean that a big one is coming? Or do small ones mean that the pressure is being released so that it can't build up high enough for a big one? Probably the small ones don't release enough energy

Figure 6.26 This aerial view shows how communities have been built without regard to the location of the San Andreas Fault (indicated by the white line).

to be good pressure relief valves. Maybe all we can do is keep good records for many years. Perhaps then we will understand earthquakes enough to predict approximately when they should occur.

But we have discovered a possible way for man to ease the danger of bad earthquakes along fault zones, and we discovered it quite by accident. In April 1962, earthquakes began occuring in the Denver area. They had Richter values of 3 to 4. They became more and more common, and eventually became everyday occurrences. In 1967, some had Richter values of 5.5. Why had they started? Finally, a geologist linked them to an important fact. The U. S. Army had begun pumping waste chemical fluid down a 3700-meter-deep well to get rid of it. The earthquakes began not long afterwards. They have stopped pumping and the earthquakes have become less and less frequent. What had happened?

The waters had lubricated the fault-zones at depth. This made movement along the faults easier because there was less friction. Earthquakes were the result. Could we control potential killers like the San Andreas Fault by pumping water down into the fault zone? It would take a lot of water. And tampering with nature might cause even worse earthquakes.

After certain underground atomic explosions, small earthquakes have occurred in the area of the blast. Perhaps even atomic power can be harnessed to release the pressure on faults.

One important thing that can be done in earthquake areas is to build the right kind of buildings. Some types stand the vibrations better than others. And it has been proven that buildings built on loose fill are damaged more than those built on solid rock. (Recall the warnings of the geologists in Alaska?) And maybe it's wise not to build on fault zones, as in Figure 6.26.

CHECK YOUR FACTS

1. What is the most common cause of earthquakes?
2. Where do most earthquakes of the world occur?
3. What is a seismograph?
4. How do P and S waves differ?
5. What is the Richter scale?
6. Can we predict earthquakes?

(1) (1) ANSWERS / Check Your Facts

1. Buildup of pressure near a fault.
2. Earthquakes are common in volcanic areas.
3. A device for detecting, recording, and measuring earth tremors.
4. The P waves are compression waves, much like sound waves. The S waves move up and down.
5. A special scale, with values from 1 to 10, for evaluating the severity of earthquakes.
6. No.

A BIG EGG—EARTH

The Earth is something like a round hard-boiled egg—cracks and layers and all. But unlike Humpty Dumpty, it is still in one piece. (2)

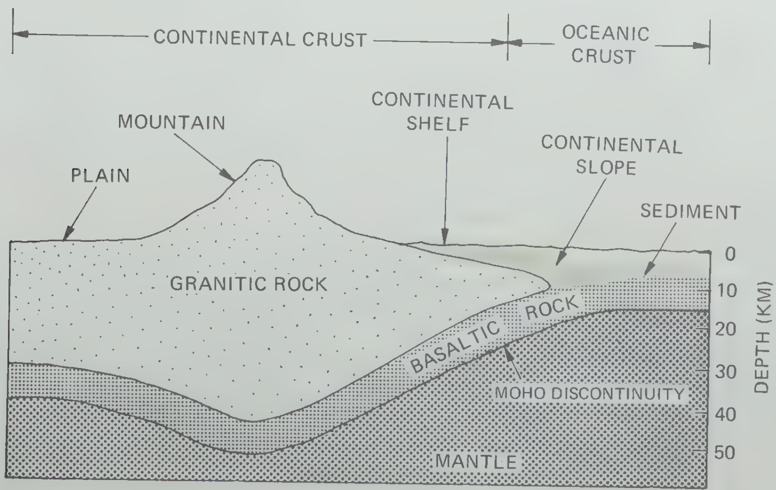
Earth scientists have made a model of the Earth based on all the evidence they can find. Most of the evidence is indirect. As earthquake waves travel through the Earth, they are reflected off the boundaries between the major layers of different earth materials or they are refracted (bent) as they pass through the boundaries. The best-studied boundary is the **Mohorovičić boundary** or **discontinuity**, named after a Yugoslav seismologist. It is called "Moho" for short (Figure 6.27). And other evidence, as strange as it seems, is provided by meteorites—more on that later. (3)

(2) Of course, Earth isn't egg-shaped—it's pear-shaped! (There is actually a slight bulge in the Southern Hemisphere which makes Earth *very* slightly pear-shaped, so slightly that it is hardly noticeable.)

(3) Our introduction to Earth's interior is simplified. This is a very complex subject.

Crust. Above the Moho is the Earth's **crust**. This is our thin "eggshell." It is only about 5 kilometers thick under the oceans. Under the continents, it is as much as 60 kilometers thick. Because S waves, which can move only through solids, can penetrate the crust, we think the crust is solid rock. By the speeds at which the earthquake waves travel through the crust, the rock type of the crust can be predicted (because we have experimented with rocks at the surface). Beneath the oceans the crust is made of basalt. The continental crust,

Figure 6.27 The Moho boundary or discontinuity is the boundary between the mantle and the crust.



however, is made of granitic rocks lying on top of basaltic rocks. The continents are like blocks of granite floating on the basalt layer. (Don't take the word "floating" too literally, however.)

In Chapter 3, when you studied magma, you may have wondered whether magma came from a molten layer beneath Earth's hard outer crust. Now you know this can't be the case. Magma at depth must occur in small, local pockets.

From Figure 6.27 you can see that the granitic crust is thicker under mountains than under plains. Mountain ranges are kind of like icebergs. They are mostly beneath the surface; only their tops stick up above the surface. The part beneath is called a root. High areas have deep roots and low areas have shallow roots. This balance between different parts of the crust is called **isostasy**, from the Latin for "equal standing." The existence of roots has been proved by the reflection of earthquake waves.

Mantle. The **mantle**, the "white of the egg," is the thickest of Earth's layers (Figure 6.28). It extends down about 2900 kilometers from the Moho to the Earth's core. Because earthquake waves travel faster in the mantle than in the crust, we know that mantle material is denser. At several places on Earth's surface, small bodies of an iron- and magnesium-rich rock called **peridotite** are exposed. Peridotites are made of olivine and pyroxene. It is probably the main rock in the mantle. Some earth scientists think that the basalts of the crust were formed by the partial melting of peridotites in the mantle.

Naturally geologists would like actual samples of the rocks beneath the crust. They are out to get them, too. Did you ever hear of the American **Mohole project**? (Not "mole hole," but "mohole.") The idea is to drill a 25-centimeter-diameter hole through the Moho (Figure 6.29) and get samples from the mantle. (Like little Jack Horner, they hope to put in their thumb and pull out a plum.)

The crust under the continents is too thick to drill through. The plan is to drill through the thinner oceanic crust near Hawaii. (The Russians are planning their own Mohole through the continental crust.) The first thing necessary is a drilling platform that won't move, even in a hurricane. Over 150 million dollars had been spent on the project by 1966. A few test holes were drilled into oceanic crust. But Congress has refused to give out any more money for the project. It will be revived, we hope.

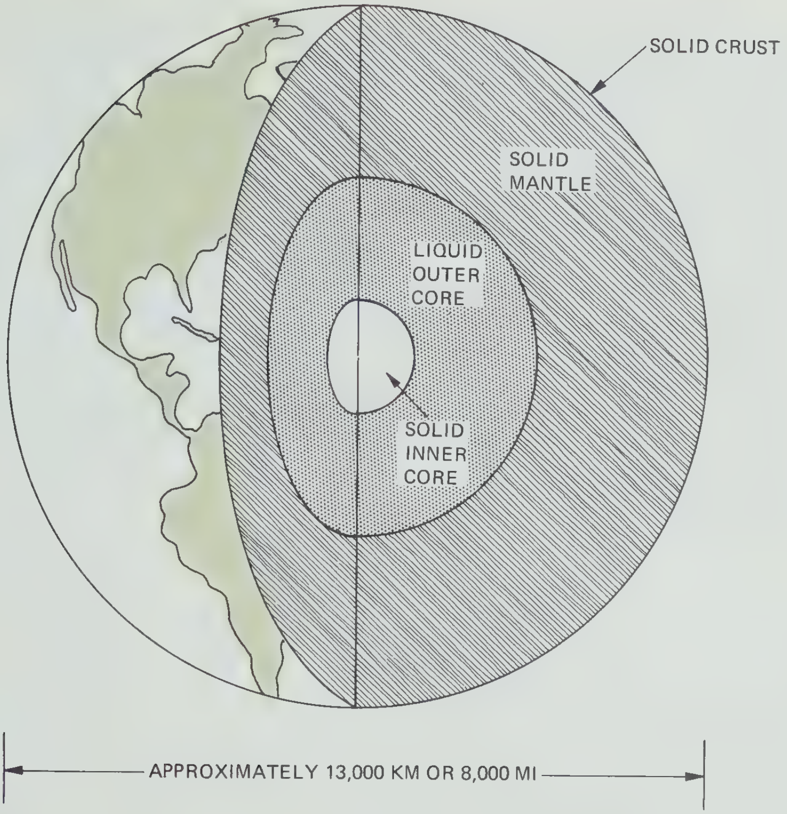
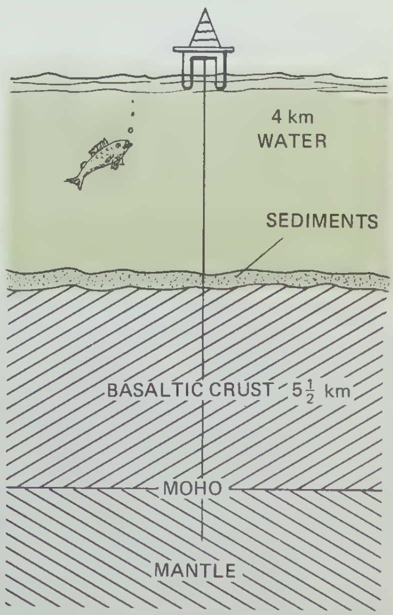


Figure 6.28 Earth, the "big egg," has a thin "eggshell" (crust), an "egg white" (mantle), and a "yolk" (core).

Figure 6.29 (below) In the Mohole project, it was proposed to drill all the way through the ocean sediments, the crust, and the Moho boundary into the mantle. The drill would bring up samples of mantle material.



Besides bringing up samples of the mantle, there would be other benefits of the project. It would increase knowledge about Earth's origin and history. It may even help us learn more about earthquakes and volcanoes. It will certainly teach us how to drill holes in deep water and thus make deep-water exploration for oil and gas possible.

activity 6.2 Isostasy

In this activity you will make models of Earth's crust. For the first part of the activity you will need ice cubes and a glass container (a graduated cylinder with a diameter slightly larger than an ice cube will work best). For the second part of

the activity you will need blocks of wood and a glass or clear plastic container wide enough so that the blocks of wood can float side by side in it. The pieces of wood should be longer and wider than they are high so they will float horizontally in the water. Three pieces cut off the end of a standard "two by four" (2 inches by 4 inches, or about 5 centimeters by 10 centimeters) will work best if they are cut about 15 millimeters, 25 millimeters, and 40 millimeters thick. For both parts of the experiment you will also need water and a ruler. (1)

For the first part of the activity, partly fill a cylinder or other container with water and float an ice cube in it. Measure how much of the cube is above water and how much is below. What percentage is below?

After the cube has melted some, measure it again. When it has become quite small, measure it a third time. How did the distance below the surface change as the ice cube melted?

From your observations, what do you predict would happen to the roots of mountains as the mountains are eroded down?

Now, the second part. Float the three blocks of wood in water and measure how much of each block is above and how much is below water.

Assume that each of the three blocks represents a portion of Earth's crust. Assume that together the blocks represent a continent with lowlands, high plateaus (high flat areas), and mountains. Using the water level in the container as sea level, sketch the blocks side by side and label them as lowland, plateau, and mountains. How does this model demonstrate the principle of isostasy?

The mantle has a density of about 3.3. Earth's crust has a density of 2.7 to 3.0. In terms of density, are wood and water reasonably good choices for representing the crust and mantle?

(1) The pieces of two-by-four should be knot-free—knots are heavier than the rest of the wood. (The thicknesses of the blocks are not critical, just so the 3 have appreciably different thicknesses.) If you desire, you could set up a similar demonstration with five wood blocks of different types of wood but with the same cross-sectional area and same weight. They will, of course, be of different lengths because of their different densities. The tops will ride at different levels, but the bottoms will be at the same depth below the water surface. This, plus the student activity, are models of the original isostasy models, which were made with blocks of metal floating in mercury. (A cabinet-making shop or the school shop should have scraps of different woods available.)

Core. Earth's **core** is not quite like the yolk of an egg. It has two parts, the inner core and the outer core. The outer core is about 2300 kilometers thick and the inner core has a radius of about 1200 kilometers. Remember that S waves can move only through solids? Well, only P waves get through the outer core. S waves don't. They enter the outer core and disappear. So what conclusion do we come to? We conclude that the outer core is not solid, but liquid. (So Earth isn't a hard-boiled egg after all.) The inner core seems to be solid. We think this is so because P waves seem to pick up speed in the inner

core. Both the inner and outer cores are probably made of iron and nickel. The temperature in the core has been estimated at 3000 to 4000°C.

Earth is denser than it looks. It is the densest of the planets, with a density of 5.52 (that is, it is 5.52 times as heavy as an equal volume of water.) We know that basalt and granite make up most of the crust. Granite has a density of about 2.7 and basalt has a density of about 3.0. So, isn't the interior of the Earth made of heavier stuff? Earthquake waves generally travel faster at depth. Therefore (in general anyway), the rocks must get denser the farther down we go.

The core seems to be the densest part of Earth. That's one reason why a core of iron and nickel has been proposed. Another reason is that metallic meteorites are made mainly of iron and nickel. We think most meteorites come from the asteroid belt between Mars and Jupiter. We also think they were probably formed when the planets, including Earth, were formed. Therefore, couldn't we expect the Earth to be made of some of the same stuff? (And stoney meteorites give us clues to the mantle material, too.)

So that's the Earth model. Some of you may be tired of our modeling. (You'd like to see some live models?) By now you have probably concluded that earth scientists use lots of models. Why don't earth scientists know things for sure? Think about that. How can you describe something you can't see, like an atom or the inside of Earth? Or something that happened long ago? Actually it is amazing that earth scientists have learned as much about Earth as they have. All things considered, you must admit that they are pretty good detectives. And they will never run out of interesting cases to work on.

CHECK YOUR FACTS

1. What is the Moho boundary?
2. How thick is Earth's crust?
3. How does the crust of the continents differ from the crust under the oceans?
4. What is the thickest of Earth's layers?
5. What is isostasy?
6. What is believed to be the main rock in the mantle?
7. What was the purpose of the Mohole project?

(2)(2) **ANSWERS** / Check Your Facts

1. The boundary between the crust and the mantle.
2. From 5 to 60 kilometers thick.
3. In thickness.
4. The mantle.
5. The equilibrium of the earth's crust maintained by a yielding flow of material between crust and mantle.
6. Peridotite.
7. To study the mantle.

APPLYING WHAT YOU HAVE LEARNED (1)

1. The islands of the East Indies are volcanic islands, with many volcanoes still active. Even Krakatoa, mentioned in the introduction to this chapter, is actively rebuilding after the tremendous explosion of 1883. Yet Java, the main island of Indonesia, is one of the most densely populated areas in the world. Why do so many people live where severe volcanic eruptions could occur?

2. Surtsey, the volcano that grew out of the ocean near Iceland in 1963, was a very explosive volcano in its early days. Great explosions repeatedly hurled hot particles of rock as high as 1800 meters. What do you think accounted for its explosiveness, compared to the rather quiet Hawaiian volcanoes, which also rise out of the ocean?

3. What would happen to a piece of steel in a dish of mercury? What would happen to you if you sat in a big container of mercury? What determines whether a material will float or sink in a liquid? Does a ship float higher in fresh water or in salt water? Why don't steel ships (and concrete boats, a recent innovation) just sink rather than float?

4. Some geologists foresee possible problems for some northwestern cities if the volcanoes of the Cascade Range become active again. Look at a map of the northwestern United States and determine which cities might be affected. Do you think the big volcanoes of the Cascades are extinct, dormant, or active? What might happen if they erupted in winter, rather than in summer?

5. We've learned that the interior of Earth is made of distinct layers—a core made of heavy material, a mantle made of lighter material, and a crust made of the lightest material. What does this suggest to us about Earth's origin?

6. Many volcanic rocks contain small holes formed by gas bubbles in the lava. In which part of a lava flow—top, bottom, or middle—would you expect to find most of these holes? Might this be used as a means of telling tops from bottoms in highly twisted and folded lava flows?

7. What are some similarities between Figures 6.12 and 6.19?

8. We've compared Earth to an egg. What are some things wrong with this simple comparison?

(1) **ANSWERS** / Applying What You Have Learned

1. Where can they go? The soil is rich. (Volcanic rock weathers quickly and becomes rich soil.) The climate is nice, and it's a lovely place! As in Sicily, the people have become fatalistic about eruptions.
2. The seawater entering the vent. Hawaiian volcanoes may have been like that originally, before their vents were formed above sea level.
3. It would float. You would float (you would also become ill). Their relative densities (weight per unit volume). Salt water is denser—therefore the ship floats higher in salt water. Even though steel and concrete are denser than water, a ship made of such materials still weighs less than the volume of water it displaces. Therefore it floats.
4. Eugene? Portland? Seattle? Others? . . . A good question. Probably most of these mountains are *not* extinct and will act up again. Much melt water from snow would cause watery, "muddy" ash flows.
5. At least at some time in Earth's history (many think Earth had a cold origin), Earth became molten and the denser material settled to the center while the lighter material rose to the top.
6. Most gas cavities would be near the tops of flows. Yes.
7. Very similar! This point will be important in Chapter 10 on Ocean Basins.
8. See page 123.

KEY WORDS

pyroclastic particle (p. 108)
cinder cone (p. 108)
composite cone (p. 108)
shield volcano (p. 108)
active volcano (p. 109)
dormant volcano (p. 109)
extinct volcano (p. 109)
basalt flood (p. 111)
batholith (p. 113)
dike (p. 113)
sill (p. 113)
fault (p. 116)
P wave (p. 117)
S wave (p. 117)
surface ware (p. 117)
seismograph (p. 117)
seismogram (p. 118)
Richter scale (p. 120)
Mohorovičić discontinuity (p. 123)
crust (p. 123)
isostasy (p. 124)
mantle (p. 124)
peridotite (p. 124)
Mohole project (p. 124)
core (p. 126)

Figure 7.1 The folded layers in this mountain can be clearly seen. What processes formed this mountain? (1)

Introductory Demonstration

Show the film, "How Solid is Rock?" (EBF) and leave plenty of time for discussion.

(1) Deposition of sediment in horizontal layers; hardening into rock; complex foldings.

chapter 7

The Crust Goes Up and Down

Earthquakes and volcanic eruptions are truly spectacular. And the energies released in such events are truly large.

Yet such quantities of energy are just like drops in a pail. Some other processes use much, much more energy. Let's look at mountain building. There are fossil sea shells high on Mt. Everest in the Himalayas. Many large mountain ranges of the world contain marine fossils in folded and broken sedimentary rocks high up. Why? The only conclusion we can come to is that the rocks were lifted up out of the sea to form mountains. And to lift thick piles of rocks wide enough and long enough to form mountain ranges must require fantastic forces! But it has happened time and time again in the geologic past. And it is happening in some places right now.

The Coast Ranges of California are not really big mountain ranges, but some of the ranges are rising at approximately

a meter per century. If you were king of the mountain and had your throne on the mountain top, would you notice that the mountains were getting higher? Probably not. Not even if you sat there for a thousand years. But if you sat there for a million years and the uplift continued, how high would your throne be? It is quite likely that someday the Coast Ranges along the western coast of North America will be the highest mountains on the continent. And they will stretch from southern California to Alaska. (Just think how great the skiing could be!)

THE DISTURBED LAYERS

Most sedimentary rocks were deposited in horizontal or nearly horizontal layers. Right? Right. But the sedimentary rock layers in Figure 7.1 are standing on end. So we might conclude that some sedimentary layers must have been deposited that way, as vertical beds. Right? Wrong.

In many areas, such as the Grand Canyon, sedimentary rocks that were laid down as horizontal units are still horizontal. In such an undisturbed pile of sedimentary rocks, would you expect the layers on top to be younger or older than the bottom layers? Your answer will probably be "Younger, of course." The answer seems simple and logical, but it was not clearly stated until 1669. Nicholas Steno, a naturalist who lived in Denmark, was probably the first person to fully appreciate the idea and say so in writing. Steno's discovery was an important one in the development of geology as a science. It showed that there was an orderly development of the rock layers.

Folds. In many places the rocks that originally were horizontal have been folded by strong forces inside Earth (Figures 7.1 and 7.2). What kinds of forces cause folding? Does it seem more likely that rocks would be folded by squeezing them (**compression**) or by stretching them (**extension**)? Think about it. **(1)(1)** Compression.

When pressure is slowly applied to rocks, they bend. If the temperature and pressure are high, as at great depths, the rocks bend fairly easily. Some highly folded rocks even look like they flowed. Under such conditions, they may actually have behaved like soft mud.

Figure 7.2 Can you tell which beds are upside down? (2)

(2) Very difficult to tell, even for a geologist.

activity 7.1 Deformation—flow or fracture?

In this activity you will observe how the substance Silly Putty behaves when pressure is applied to it slowly and when pressure is applied to it quickly.

Put a ball of Silly Putty on a desk top overnight. What happened?

Put a ball of Silly Putty under a heavy book and watch it react to the pressure of the heavy book. What happens? Strike a ball of Silly Putty with a hammer. What happens? (Make sure you pick up *all* the pieces afterwards!) Repeat these two experiments with refrigerated balls of Silly Putty. What happens? Repeat with warm balls of Silly Putty. What happens?

How can the behavior of Silly Putty be compared to the behavior of rocks?

Would you expect rocks under pressure near the surface of Earth to behave differently from similar rocks buried under thousands of meters of other rocks?

Most highly folded rocks are found in the mountains, or in areas that were once mountainous. In some mountain ranges, such as the Rockies, some sedimentary beds are nearly upside down (Figure 7.2). Older rocks are on top of younger

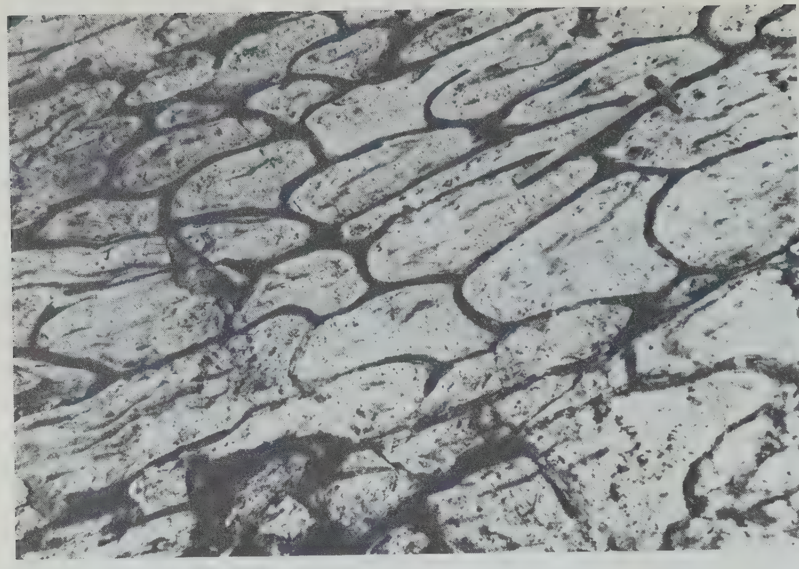


Figure 7.3 When lava flows into water, it cools quickly and forms "pillows." The pillows have rounded tops and pointed bottoms.

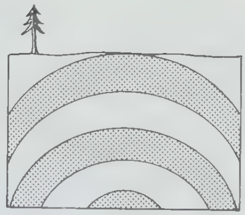
(1) Yes, because it is an anticline; but we have no way of knowing if oil is underneath.

(2) Only curved cross-beds can be easily used to identify tops. These cross-beds are concave upward. (As sand is deposited in a cross-bed, it tends to fall downward under the influence of gravity. Hence, cross-beds won't be convex upward.)

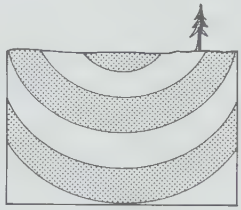
Figure 7.4 Would this be a good place to drill for oil?

rocks. How can we tell? There are several kinds of evidence. For example, cross-beds might tell us which side of a bed was originally up. (How?) Graded beds can also tell us this. (How?) (2) Another aid is **pillowed lava flows** (Figure 7.3). (3)

All tilted rock layers are parts of larger folds. There are two main types of folds—upfolds and downfolds. The upfolds are called **anticlines** and the downfolds are called **synclines**. They commonly occur together—anticline, syncline, anticline, syncline. You already know from Chapter 4 that anticlines are good traps for oil and gas. Figure 7.4 shows how a large eroded anticline looks from an airplane.



ANTICLINE



SYNCLINE

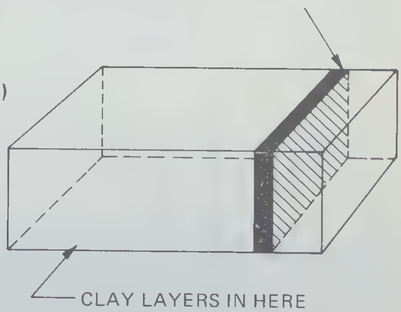
(3) Graded beds are easier to use. In them, the coarser grains are on the bottom. In pillowed lavas, good pillows with rounded tops and pointed bottoms are useful, since the lava pouring out under water "balls up" as it cools (much like a spoonful of hot fudge dropped into a glass of cold water). The points on the bottom form as the pillow forms in between and on two earlier pillows.

activity 7.2 *Making folded layers in a "squeeze box"*

In this activity you will use layers of modeling clay to represent sedimentary rock layers. You will need modeling clay (at least two colors); a rectangular plastic or glass container with an open top (about 10 to 15 cm long, 5 to 10 cm wide, and 5 to 10 cm high); a block of wood or other material that is as wide and high as the container but loose enough to slide within the container and grease, Vaseline, or some other lubricant.

Flatten the different colored clay into layers about 1 to 2 cm thick, as wide as the container, and about 3 cm shorter than the container. Grease the inside of the container, and then put three or four layers in it, on top of one another. Slowly push the block against the layers until they start to fold. As the pressure is continued, watch the layers deform. What kinds of folds formed? Anticlines or synclines? Are the sides of the folds gentle or steep, or first gentle and then steep? (4)

Straighten out the layers and reassemble as before. Push quickly rather than slowly. Any difference in the results?



Faults. Under different conditions, instead of bending, rocks can break and change position. Continued pressure causes movement along some cracks. Such cracks, along which the rocks move, are called **faults**. Some faults are due to compression. Others are due to extension.

(4) Warm clay works better than cold clay. If students are having trouble making it fold, have them use thinner layers. You might demonstrate folding with two or three sheets of colored foam (sponge) rubber.

Because there is often crushed rock along fault zones, these zones serve as pathways for hot waters and magmas. Therefore, many dikes and ore deposits have been formed along faults. Miners taking out these ores have logical names for the rock on the two sides of a nonvertical fault. (Most faults are not vertical, but are at some angle.) They call the side hanging above them the **hanging wall** and they call the side under their feet the **footwall** (Figure 7.5). These miners' terms are also useful to geologists in describing faults.

If the hanging wall has gone *down* relative to the footwall, the fault is called a **normal fault** (Figures 7.6 and 7.7). The rocks on the top side have "fallen down" relative to the footwall. (Note that we say *relative* movement. Isn't it possible that the footwall went up rather than the hanging wall going down?) Which type of force, compressional or extensional, would cause most normal faults to form? Think about it—and don't forget the effect of gravity on the hanging wall side.

If the hanging wall has gone *up* relative to the footwall, the fault is called a **reverse fault**. The rocks on the top side or hanging wall have been "pushed up" relative to the footwall.

If a fault isn't a steep one, older rocks from below may be pushed up onto younger rocks, rather than just next to younger rocks. So this is another case of older rocks being on top of younger rocks. Scratches caused by rock scraping rock along the fault help us to identify it as a fault or a zone of faulting. Good field studies will show whether the older rocks are on top of the younger rocks because of faulting or because of folding.

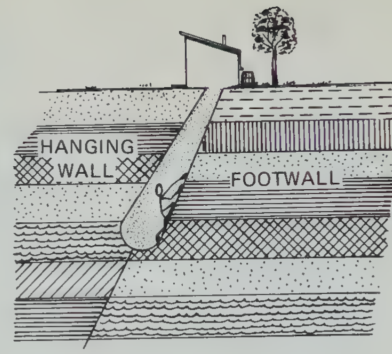


Figure 7.5 Has the hanging wall moved up or down relative to the footwall? **(1)**

(1) Up.

Figure 7.6 A normal fault (top), a reverse fault (middle), and a fault involving horizontal movement (bottom).

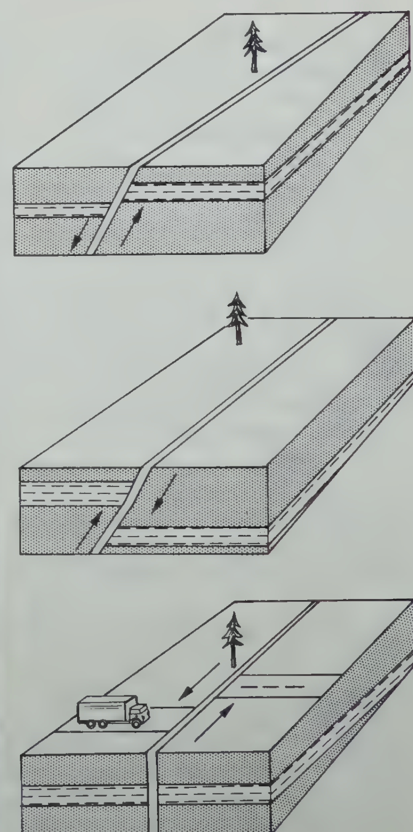


Figure 7.7 There has been about 10 meters of vertical movement on this recent fault. What evidence can you find to indicate that this fault happened recently? **(2)**

(2) You can tell this is a recent fault because erosion has not yet obliterated its sharpness.

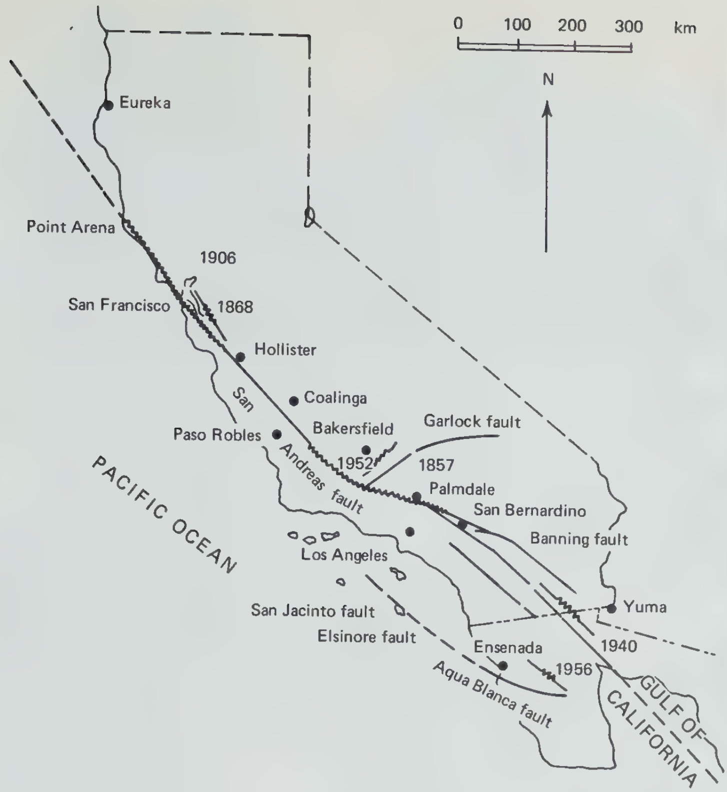


Figure 7.8 The long San Andreas Fault is one of the best-studied faults in the world. The movement is mainly horizontal, with the land west of the fault moving northward.

Some low-angle reverse faults have had tens of kilometers of movement along them. Along some normal faults and reverse faults, there have been movements of hundreds or thousands of meters. But along most faults, the movements range from a few centimeters to a few meters.

A third major type of fault involves horizontal movement rather than vertical movement (bottom of Figure 7.6). One of the best-known examples of a fault with horizontal movement is the San Andreas Fault in California (Figure 7.8). Actually it is not a single fault, but a fault zone composed of many parallel faults. And no one knows along which fault the next movement will be.

The land on the west side of the San Andreas Fault moves north whenever there is movement along the fault. (Repeated surveys across the fault zone also show that the west side is moving north nearly continually, about two centimeters per year.) Friction of rock on one side of a fault against rock (3) on the other side tends to prevent movement, and so pressure builds up. When the pressure becomes greater than the friction, there is movement along a fault. Some geologists estimate

(3) The surveys consist of a network of survey points extending several miles east and west of the fault. The same points are surveyed many times. The northward movement of the land west of the fault is continued, but adjacent to the fault the land moves only when the friction of rock against rock is overcome by the forces. Then there is a sudden movement *and* an earthquake. (Obviously the rocks are being bent if they don't move near the fault but do move a distance away from the fault.) You might ask your students how long they think California has been having earthquakes. They should say 150 million years!

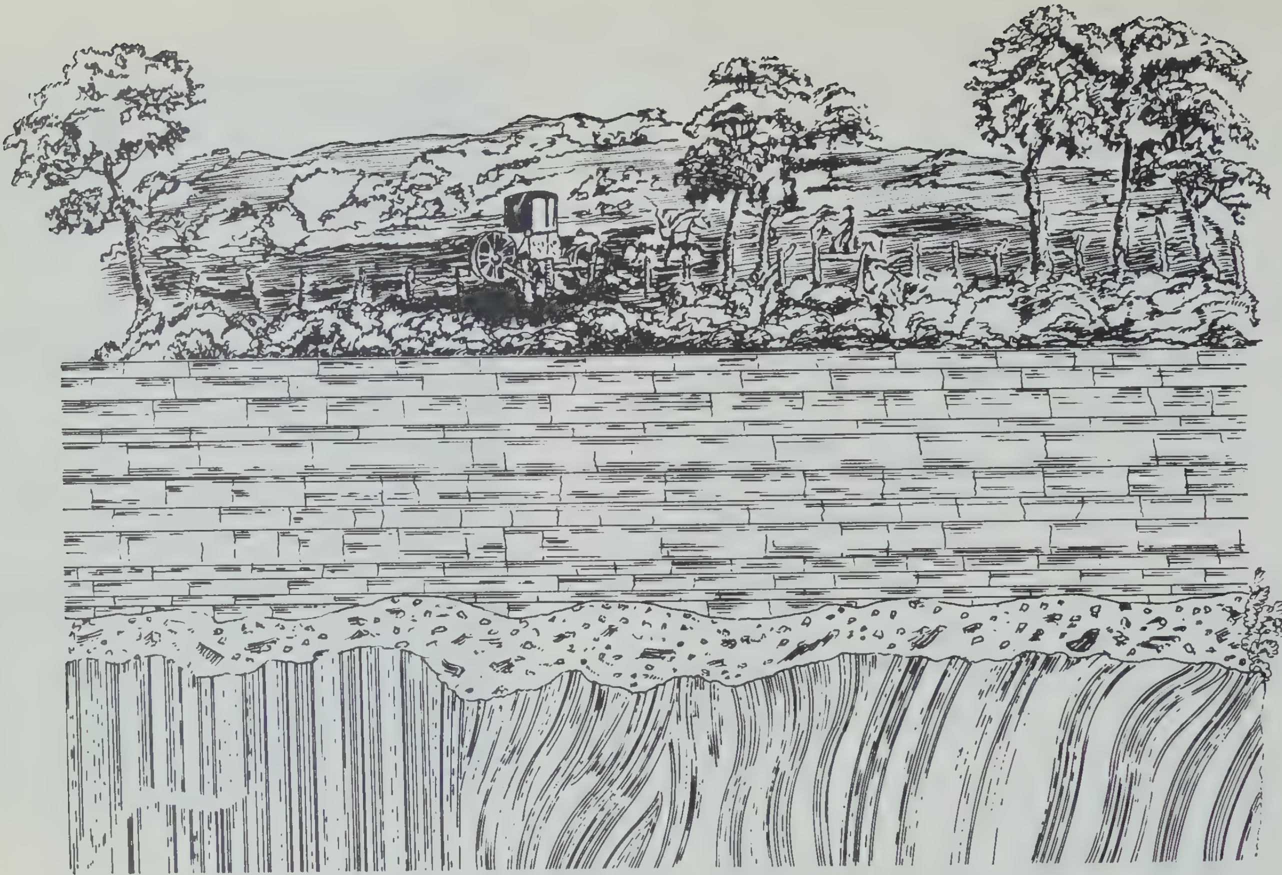


Figure 7.9 This buried surface of erosion in Scotland was studied by James Hutton.

that the west side of the San Andreas Fault has moved northward 600 kilometers in the last 150 million years. Note from the map in Figure 7.8 that Los Angeles is west of the San Andreas Fault and San Francisco is mostly east of it. Isn't Los Angeles getting closer to San Francisco? At the present rate of movement, how soon will they be side by side? (And that will probably happen long before western California slides into the sea, as some "prophets" have predicted.)

Faults very similar to the San Andreas Fault are found in Japan, the Phillipines, New Zealand, and Chile. Along all of them, the movement is such that the Pacific Ocean basin seems to be rotating counterclockwise. Great things are happening around the Pacific Ocean! What other features are found around the Pacific? (Remember Chapter 6!)

Buried surfaces of erosion. James Hutton in his field studies found places where horizontal rocks were lying on steeply dipping rocks (Figure 7.9). He interpreted the surface above the tilted beds as representing "the remains of an ancient world." He realized that the steep beds had (1)

(1) Hutton fully realized the significance of the horizontal rocks on steeply dipping rocks and stated that the tilted beds had been tilted first and later eroded. This, he said, must have taken quite a bit of time. Earlier scientists had attributed such relationships to other causes; for example, to lower rocks which have fallen and become tilted by the action of gases escaping from within the earth.

once been horizontal. (Wouldn't we have, too?) In back of this reasoning is our old familiar statement—the present is the key to the past.

Hutton had correctly identified a surface of erosion within the rock pile. The angle between the sedimentary rock units Hutton studied makes this kind of surface of erosion easy to recognize. Some others are not so obvious (Figure 7.10). Sedimentary rocks can be found on top of weathered igneous and metamorphic rocks. Then we must be sure that the igneous rocks didn't intrude the sedimentary rocks. (How can we tell this?) The hardest surface of erosion to identify is where (2) the rock layers above and below the surface are parallel to each other (Figure 7.11). How can such surfaces be recognized? Sometimes the different ages of the fossils in the different layers provide the only clue that the surface is an erosional surface. Sometimes old soils are present.

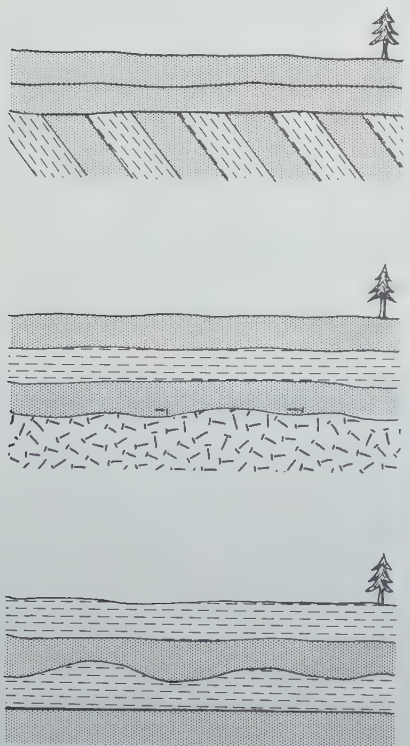
How are surfaces of erosion formed? First, don't the rocks have to be lifted above sea level? The uplifted area may be very large. These broad uplifts are commonly slow and gentle

(2) Students commonly make the mistake of calling all igneous-sedimentary contacts surfaces of erosion. A true igneous contact will show some contact metamorphism. A surface of erosion may have a rubbly zone, a basal conglomerate, or an old soil.

Figure 7.10 (below left) Of these three buried surfaces of erosion, which is the easiest to identify? (3)

(3) The top one.

Figure 7.11 (below right) A buried surface of erosion is present at the base of the dark-colored limestone cliff, where the more gentle slope of shale and limestone begins. Without studying the fossils in these rocks, geologists might not have learned about this eroded surface, since it is nearly parallel to beds above and below it.



and may raise the area only a few hundred meters. But this is commonly enough to lift a pile up from beneath the sea. Once the pile is out, erosion usually starts. Later new layers of sediment are deposited on the erosion surface. Of course, if the new beds are marine, the area must sink below sea level before the deposition. But if the beds are nonmarine, this need not happen.

Some broad uplifts may lift sedimentary rocks a kilometer or more. The result is a high area such as the Colorado Plateau. In broad uplifts, the rock layers are only slightly folded, if at all. Look back at Figure 2.16 of the Grand Canyon, which is on the Colorado Plateau. How many major surfaces of erosion can you spot within the rock pile? You won't find them all without more information on the fossils and ages of the rocks.

During the more violent uplifts that form large mountain ranges, the rocks are much more messed up. They are folded, faulted, and then maybe folded and faulted again. The areas of uplift are commonly long and narrow. The amount of uplift is also much greater than in the broad gentle uplifts; and the greater the uplift, the greater the erosion. The uplifts may occur at many different times. Figuring out the history of such an area is one of the most difficult jobs of a geologist.

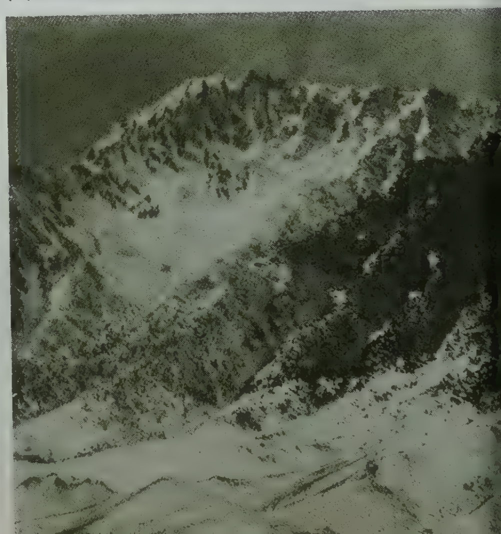
CHECK YOUR FACTS

1. What types of force produce folds?
2. How are faults produced?
3. What are some clues you might use to help you recognize a buried surface of erosion?

(1)(1) ANSWERS / Check Your Facts

1. Compression.
2. Compression or extension.
3. The angle between the sedimentary rock units. Sedimentary rocks on top of igneous rocks. The presence of fossils or old soils.

(2) Erosion.



MOUNTAINS

Types of mountains. There are many types of mountains (Figure 7.12). You already know about one type, the volcanoes. Another type is a **fault-block mountain**, produced largely by faulting. The eastern side of the Sierra Nevada in California is a steep normal fault (Figure 7.13). Total movement on this fault is estimated at more than 7700 meters. Of course the Sierra Nevada isn't that high now. (Why not?) Many small mountain ranges in Nevada,

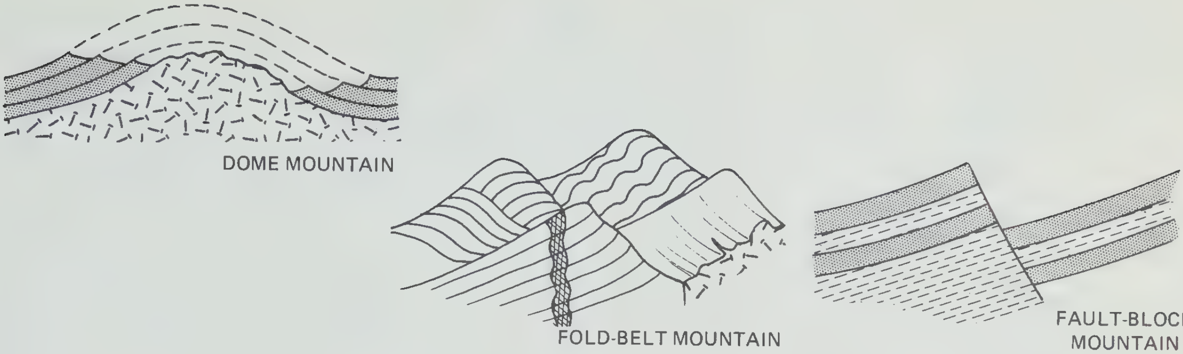


Figure 7.12 Various types of mountains.

Utah, and New Mexico are also faulted mountains, as are the spectacular Grand Tetons of northwestern Wyoming and the Wasatch Mountains of Utah.

A third type of mountain is a **dome mountain**. In this type of mountain, the rocks are simply "domed up" or pushed up by forces within the crust. They aren't very folded or faulted, but just arched upward. The Black Hills of South Dakota and the Adirondacks of New York are fine examples.

But we haven't yet mentioned the big mountain ranges of the world. What about the Rockies, Appalachians, Alps, Andes, and Himalayas? They are all **folded mountain ranges**—the longest, widest, and highest. Some of the major mountain ranges of the world are shown in Figure 7.14.

Geosynclines. How do folded mountains form? Folded mountains have formed in places where the sediments piled up until they were many kilometers thick—even ten to fifteen kilometers thick! Evidently the sediments accumulated slowly,

Figure 7.13 The eastern side of the magnificent Sierra Nevada.

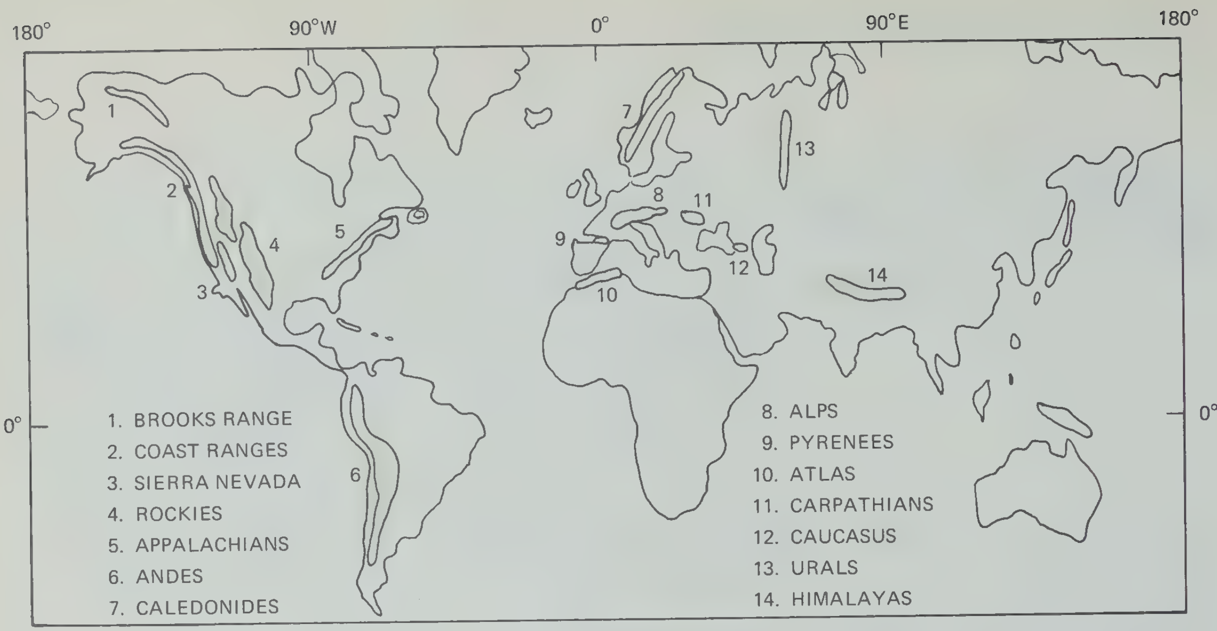


Figure 7.14 Some of the major mountain ranges of the world.

but steadily. They were deposited in long, narrow basins we call **geosynclines.** ("Geosyncline" means "earth syncline." A geosyncline is by definition hundreds of kilometers long.) As the sediments in a geosyncline pile up thicker and thicker, the crust beneath bows downward. Finally the lowest sediments can be buried so deeply that they melt to form magma. Some magma comes up to the surface and volcanoes form, but most cools at depth as large batholiths. ("Home, Sweet Home" to a batholith is the bowels of a folded mountain range.) In many folded mountains, the sedimentary rocks overlying the batholiths are intruded, folded, faulted, metamorphosed, and uplifted. They get the works.

Which came first—the chicken or the egg? We can also ask: which came first—the geosyncline or the thick pile of sediment? The American geologist James Hall (1811–1898) (1) studied the thick pile of sedimentary rocks in the northern Appalachians and noticed that most of the rocks showed evidence of having been formed in shallow water. (What kind of evidence would suggest this?) He thought that the great weight of the sediment caused the crust to sink in that area. When this happened, he said, a shallow basin was formed. Once a basin formed, more sediment was washed into it. So it sank more under the additional weight of the new sediment.

(1) Hall and Dana were two of the earliest famous American geologists. Geosynclinal theory was one of the first major contributions of American geologists, with the Appalachian area providing the evidence.

James Dwight Dana (1813–1895), an American geologist and mineralogist, named the long basins geosynclines. But

he argued with Hall. Dana said that the weight of the sediments couldn't cause the sinking. According to him, a geosyncline sank because it was a zone of crustal weakness. Because it sank and became a low area, the sediments were washed into it. So which came first—the thick sediment or the geosyncline? Most geologists now think that Dana was more correct.

Are there any modern geosynclines that are now filling with sediment? The north part of the Gulf of Mexico may be one. Sediment is being deposited there. Oil wells have been drilled in that area to depths of about 8 kilometers, where they "bottom" in quite young sedimentary rocks. There must be much more rock below. Does the thick pile of sediment suggest that this is the site of a geosyncline? Oceanographers have found thick piles of sediment at the base of the continental slopes. For example, both the eastern and western continental slopes of North America have thick sediments at their bases. Could such places be geosynclines in the making? And some scientists have suggested that deep trenches in the oceans (Figure 1.7) are geosynclines that haven't yet filled with sediment.

Mountain building. But what actually causes folded mountains to form from a geosyncline? Why is there a geosyncline with thick sediment? Why is the thick pile of sedimentary rocks later uplifted to form a mountain range? What causes the sinking first, and then the uplift later? We don't know for sure, but we've got ideas.

One old theory of mountain building was that the Earth is shrinking. According to this theory, the interior of Earth is cooling and is getting smaller, causing the harder outer crust to wrinkle up and form mountains. But if this were so, shouldn't mountains be scattered all over Earth's surface, like the wrinkles on the skin of a dried-up orange or prune? (Are they?) And why should the crust sink first rather than buckle upward first? This theory has to be discarded.

A more recent theory is that the rocks at the base of Earth's crust change. The change is from basalt to a heavier rock called **eclogite**. There is no chemical change. But, depending on the pressures, the minerals change. (Remember, minerals are stable only in the environment in which they are formed.) What minerals are in basalt? (Look at Figure 3.3 again.) Eclogite is made of garnet and an unusual kind of pyroxene. Because eclogite is a heavier rock than basalt, it

takes up less space than basalt. So when basalt changes to eclogite, the crust above the spot sinks a little. (A geosyncline?) What would happen if, after the geosyncline has filled with sediment, the eclogite changes back to basalt? Wouldn't the crust rise? (A mountain range?) Laboratory studies indicate that this change from basalt to eclogite and eclogite to basalt is very possible. But whether it happens in nature is hard to prove. The Mohole project might have helped to settle this question.

In Chapter 10 you will study continental drift, the theory that continents have moved on Earth's surface. One theory for mountain building uses drift as part of the explanation. The Rockies and the Andes may have formed on the front or "bumper" edge of North and South America as those continents drifted westward. But what about other mountains, like the Appalachians—did North America once drift eastward, too? The Alps may be the result of the collision of Africa and Europe, and the Himalayas may have formed as India collided with Asia. Recent evidence suggests that movements of parts of Earth's crust may indeed have been an important cause of mountain building. This theory is very complicated, but is also very interesting!

But what could *cause* continental drift? Could there be movement of rock at depth, in the mantle, and could this move the overlying continents? Could rock down in the mantle, where it is hot and the pressure is high, actually "flow"? Theoretically, rock under such conditions can move like boiling water in a pot, but very slowly. In a pot of boiling water, hotter water rises and cooler water sinks, forming circulating currents called **convection cells**. There is some evidence that convection cells exist beneath Earth's crust. Above the sinking part of a cell, the crust would be dragged downward. (A geosyncline?) And if the cell stopped, the light sediment and magma at depth would rise. (A mountain range?) Or, the upward-moving part of a cell could cause the uplift.

In the last few years, the idea of convection cells has been developed further. Scientists have theorized that Earth's surface is broken up into a number of very big crustal plates. Convection cells beneath the plates provide the power to move the plates. The continents are simply passengers on the plates, which are larger than continents. Many geosynclines were apparently located on the edges of continents. Could they have formed where two plates came together and the oceanic plate was forced downward, under the plate with a continent

at its edge? You will read more about this exciting topic in Chapter 10.

In summary, we don't know exactly what causes folded mountain ranges to form. Perhaps we shall never know. But in recent years scientists have gathered much new information that is leading to better theories. Certainly it's interesting and fun to keep trying to find the answers.

CHECK YOUR FACTS

1. What are four kinds of mountains?
2. What is a geosyncline?
3. What may have caused the folded mountain ranges?

(1)(1) **ANSWERS** / Check Your Facts

1. Volcanoes, fault-block mountains, dome mountains, and fold-belt mountains.
2. A long, narrow basin.
3. One theory is the clashing of crustal plates.

APPLYING WHAT YOU HAVE LEARNED

1. Figure 7.3 shows pillowed lavas. Assume you are studying an exposure of pillowed lavas that are now vertical due to folding of the rocks. What features would indicate tops of pillows and what features would indicate bottoms of pillows?

2. Scratches caused by rock scraping against rock along a fault plane are clues that help geologists determine the type of movement on the fault. How would the scratches differ if movement along the fault had been horizontal, compared to the case where movement had been vertical? How would you explain movement along a fault that has neither vertical nor horizontal scratches, but instead has inclined scratches? How would you explain movement along a fault that has both vertical and horizontal scratches on the same rock surfaces?

3. State two explanations for older rocks being found on top of younger rocks.

(2)(2) **ANSWERS** / Applying What You Have Learned

1. See annotation (3) on page 135.
2. If movement was horizontal, scratches will be horizontal; if movement was vertical, scratches will be vertical. If scratches are inclined, movement was neither horizontal nor vertical. If both horizontal and vertical scratches exist on the same fault plane, the fault has had two kinds of movement—and commonly geologists can tell which set of scratches is the latest. (Once a fault has formed, it is a zone of weakness along which movement can occur over great periods of time.)
3. Either a low-angle reverse fault (gentle dip) along which older rocks have been moved up over younger rocks, or a part of an overturned fold in which the rocks are upside down.

KEY WORDS

compression (p. 132)
extension (p. 132)
pillowed lava flow (p. 135)
syncline (p. 135)
anticline (p. 135)
fault (p. 135)
hanging wall (p. 136)
footwall (p. 136)
normal fault (p. 136)
reverse fault (p. 136)
fault-block mountain (p. 140)
dome mountain (p. 141)
folded mountain range (p. 141)
geosyncline (p. 142)
eclogite (p. 143)
convection cell (p. 144)

Figure 8.1 The Grand Canyon of the Yellowstone clearly shows that erosion and other processes are leveling the crust.

Introductory Demonstration

Show the film loop "Cavern Formation" (W), and lead the discussion to other causes of levelling.

chapter 8

Leveling the Crust

Every valley shall be lifted up,
every mountain and hill brought down;
rugged places shall be made smooth
and mountain ranges become a plain.

Isaiah 40:4

Nathaniel Hawthorne once wrote, "Mountains are Earth's undecaying monuments." He was wrong. You and I will spend but a short time on this Earth. A mountain will spend a much longer time. But as surely as you and I must go, so must the mountain go. Water, wind, and ice, acting under the influence of gravity, wear down and level Earth's surface. The high places are lowered and the low places are filled in.

This leveling, like mountain building, goes slowly. Yet over millions of years, the results are impressive. For example, geologists estimate that the Colorado River took between one

and ten million years to cut the Grand Canyon. That grand cut is more than a mile deep (about 1.7 kilometers deep). And the Colorado will cut still deeper unless man builds too many dams on the river.

Assume that for some reason Mother Earth's internal energy were gone. Internal forces would no longer raise land masses or form volcanic peaks and highlands. Slowly but surely all of Earth's land surfaces would be worn down to sea level. Fortunately for us, these internal forces have been active throughout Earth's history. They have kept us from having a dull, flat Earth, as well as wet feet. Certainly Mother Earth has maintained a neat balance between building the crust up and tearing it down!

LEVELING THE LAND

You've seen running water in a creek or gutter. Didn't it loosen bits of dirt and sand and carry them downhill to lower areas? You were watching **leveling**, and it is a simple process. We can see it taking place all around us.

Leveling involves three major processes—**weathering**, **erosion**, and **deposition**. Weathering, as you learned in Chapter 4, breaks rocks into smaller pieces. This loose sediment is eroded, or moved, from the place where it formed. It is moved by the work horses of erosion—water, wind, and ice. And the sediments themselves act as tools, wearing down **(1)** the rocks along their paths. Water, wind, and ice without such tools can cause little if any wear on solid rocks. Just as man uses tools to tear down a house, nature uses tools to wear down a rock. Finally, the sediments are deposited at some place that is lower than the place they started from.

(1) You might ask the class at this point whether they think water, wind, or ice is the most important agent of erosion. But don't tell them yet whether they're right or wrong.

Gravity. Gravity is behind all erosion. Wherever land stands higher than its surroundings, sediment will move downhill under the influence of gravity. Usually, running water does the moving; sometimes it's glacial ice or wind. But gravity can do it alone, too. Pebbles and boulders do roll down hills without any help from water, wind, or rock-rolling students. Piles of loose rock at the bottoms of most cliffs are evidence that this happens (Figure 8.2).

Some material moves downhill very slowly (Figure 8.3), but some moves very fast. We've all read or heard about the

Figure 8.2 Steep piles of angular blocks of rock are common sights in mountainous areas.

Figure 8.3 As these trees are growing up, the soil in which they are growing is slowly moving downhill, causing the trees to grow up with curved trunks.

death and destruction that **avalanches** and **landslides** cause in mountainous areas. Avalanches are sliding masses of ice, snow, or rock. Landslides, as the name implies, are composed of land—soil and rock.

A large landslide occurred in the Alps in Italy in 1963. It crashed into a man-made lake behind a 260-meter-high dam, and caused waves that were nearly 100 meters higher than the dam! The dam didn't break, but obviously the water went over the top. It rushed down the long valley below the dam, traveling 20 kilometers in seven minutes. All buildings (2) in its path were destroyed and nearly all the people—2600 of them—were killed. Surveys during the first three years after the dam had been built showed that the nearby ground was moving downslope at the rate of 1 centimeter per week. And a few weeks before the landslide, heavy rains had upped this rate to 1 centimeter per day! The bedrock in the area is folded and fractured limestone and shale. The shale became soaked with water, and finally it let go. The dam should never have been built.

(2) Students might like to calculate the speed of the water below the dam.

CHECK YOUR FACTS

(3)

1. About how long did it take the Colorado River to cut the Grand Canyon?

2. What are some means by which sediment is moved, other than by water?

(3) **ANSWERS** / Check Your Facts

1. Between 1 and 10 million years.
2. Gravity, glacial ice, or wind.

RUNNING WATER

The water cycle. Do you know how much water falls on the land each year as rain and snow? Only about 146,000 cubic kilometers! What happens to the rain after it lands? Some "runs off" or flows downhill on the surface. Some soaks into the ground. Some evaporates (enters the atmosphere as water vapor), and some is used by plants and then given off through their leaves to the atmosphere as water vapor. If we could follow an individual water molecule, it might first run off, then soak into the ground, then enter the atmosphere, and then fall again in a raindrop or a flake of snow.

We have followed our chosen molecule along what is called the **water cycle** (Figure 8.4). There are many natural cycles—you've already studied the rock cycle. But few cycles are as important to man as the water cycle, for water and its (1) movements are basic to all life on Earth. You have already learned that water is necessary for the chemical weathering that makes soil out of solid rock. Most of this chapter deals with erosion and deposition of sediment by water and ice.

(1) Someone may suggest that the food cycle is most important, or the biological cycle. However, without the soil, these cycles wouldn't exist.

Erosion by running water. Rain water that runs off or flows away from its landing point is of special interest to us. Why? Because it erodes and changes the shape of the landscape. We all know that water seeks its own level. (What is the lowest level to which water can flow?)

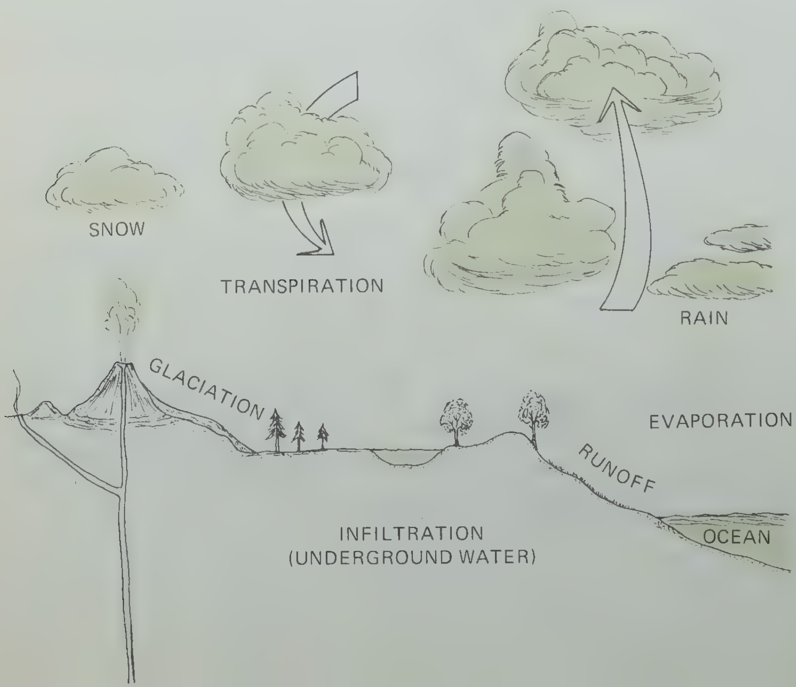


Figure 8.4 Energy from the Sun causes water to evaporate (move into the atmosphere as water vapor). Plants also pass water vapor into the air, a process called transpiration. The water vapor eventually condenses and falls as rain and snow. All these processes together make up the water cycle.

Have you seen raindrops fall and cause a splash in a mud puddle or in wet mud? An individual raindrop won't do much damage to a granite boulder, but it can kick mud around. And as the countless drops begin to move downhill to lower areas, they join together and form thin sheets of water called **sheetwash**. These in turn form tiny trickles. From tiny trickles come larger trickles, then small creeks, and eventually large rivers. Yet it is the sheetwash and the trickles of water that pry loose and carry most of the clay, silt, and sand. To be sure, rivers move much sediment, acting as large transportation agents. But rivers would have little business if they moved only the water that falls directly into their channels.

Drainage basins. The area each river system drains, or gets its water from, is its **drainage basin**. Most rivers and their tributaries drain small areas (Figure 8.5). Large rivers, however, carry water out of very large areas. For example, the Mississippi River, the largest river in North America, carries to the sea one third of all the runoff from the 48 states. It and its tributaries drain an area of over $3\frac{1}{2}$ million square kilometers. The Mississippi River is big, but the Amazon, the world's biggest river, carries *twelve* times as much water. Its

Figure 8.5 A small drainage basin looks like this from the air.

lowest volume, during the dry season, is about equal to the Mississippi's volume at flood stage! It discharges fresh water into the sea at the average rate of about eleven billion liters of water per minute. That's enough water each day to cover Texas to a depth of about 2.5 centimeters or New Jersey to a depth of about one meter.

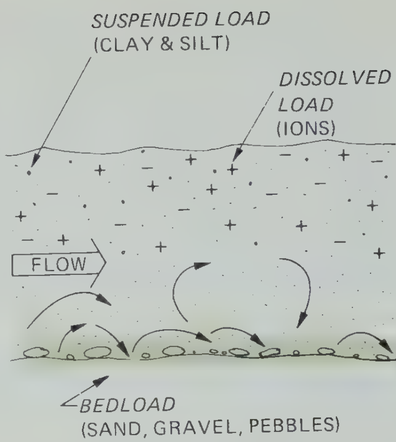


Figure 8.6 All streams transport materials in the way shown here. The amounts of each type of material vary with the speed and amount of water in the stream.

Stream transportation and deposition. Streams carry their cargos of Earth materials in three different ways, as shown in Figure 8.6. (1) Ions are dissolved in the water and carried in the water, invisible to us; (2) clay, silt, and sometimes fine sand are carried suspended in the water; and (3) larger particles such as coarse sand, gravel, pebbles, and boulders are rolled, bounced, and pushed along the bottom. (They are generally too heavy to take the delightful trip a small silt grain enjoys.) The amounts of each type vary with the speed and amount of water in the stream, and therefore with the seasons. When there is little rainfall, streams move slowly and may carry mostly ions and few particles. When there is more water, the particle load increases.

When the water and its load finally reach a lake or sea, **(1)** the speed of the water decreases very rapidly. When the running water slows or stops, it cannot help but drop its load of particles. At the Gulf of Mexico, where the Mississippi drops the final part of its load, a broad deposit called a **delta** has **(2)** formed (Figure 8.7). The sediment beneath the Mississippi's present delta has already accumulated to a thickness of more than 10 kilometers, partly because the area is slowly sinking. **(3)**

Most rivers deposit much of their load before they reach a body of standing water. Streams coming out of high mountains slow down when they reach the flatter ground at the base of the mountains. There they drop their loads of suspended sediment in the form of large fan-shaped deposits called **alluvial fans**. And since rivers generally drop part of their load wherever they slow down appreciably, most rivers also **(4)** have many deposits of sediment along their valleys.

(1) Obviously, the speed of water changes at many places other than lakes or seas, but this is perhaps the easiest to understand.

(2) The word comes from the Greek letter delta (Δ). The Nile delta is a classic one.

(3) The delta has moved through time. Only a small part of the 10 km of sediment beneath the delta is due to earlier stages of the delta. The remainder is made of marine beds. (See "geosynclines" in Chapter 7.)

(4) See Figure 14.11, in which alluvial fans are clearly visible. A stream rushing down the steep gradient of a Sierra Nevada valley carries a big load of sediment. As it issues from the mouth of the valley onto the plain, it quickly slows down and drops its sediment, which forms a fan-shaped deposit with the apex of the fan at the mouth of the valley. The fans overlap one another in Figure 14.11, so no perfect, single fan is seen.

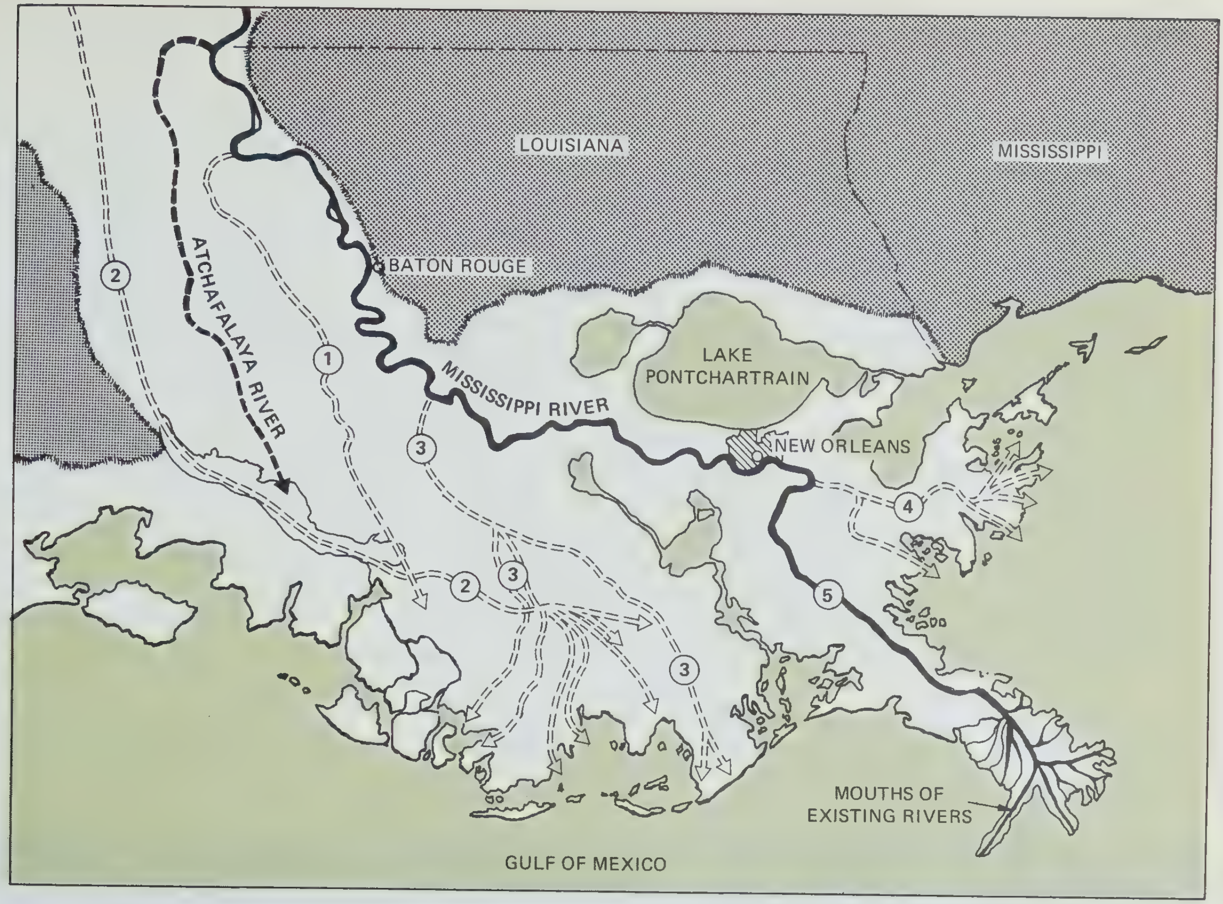
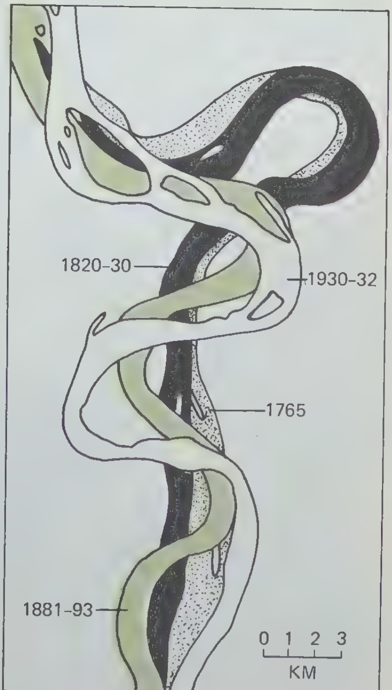


Figure 8.7 (above) Various courses of the Mississippi are shown by the numbers, 1 being the oldest (about 3000 years ago). The river is now slowly shifting to the Atchafalaya course.
Figure 8.8 (right) Various modern Mississippi courses are shown.



River valleys. If a geologist said to you, "Rivers have formed the valleys in which they flow," would this seem logical? Man has not always thought so. The Navajos have a legend that the god Yé dragged a big stick over Colorado and Arizona, forming the Grand Canyon in which the Colorado River now flows. As recently as 1800, geologists thought that rivers flowed in valleys because the valleys were low areas that existed before the rivers formed. But now we know that a river carves its own valley.

And once a river has carved its valley, does it always follow the same course? The Mississippi River hasn't, as you can see in Figures 8.7 and 8.8. It has been more curvy (longer) at certain times and less curvy (shorter) at other times. New curves are formed and old ones are cut off. Mark Twain, who was a riverboat captain as well as a writer, wrote in his *Life on the Mississippi:*

In the space of 176 years, the Lower Mississippi has shortened itself 242 miles. That is an average of a trifle over one mile and a third per year. Therefore, any calm person, who is not blind or idiotic, can see that . . . just a million years ago next November the Lower Mississippi River was upward of 1,300,000 miles long, and stuck out over the Gulf of Mexico like a fishing rod, and by the same token any person can see that 742 years from now the Lower Mississippi will be only a mile and three-quarters long, and Cairo [Illinois] and New Orleans [Louisiana] will have joined their streets together, and be plodding comfortably along under a single mayor and a mutual board of aldermen. There is something fascinating about science. One gets such wholesome returns of conjecture out of such a trifling investment of fact.

Figure 8.9 When your equipment setup looks about like this, you are ready to measure "stream velocity." Someone should keep the jug or pail at the upper end filled to about the same level at all times during the velocity measurements.

activity 8.1 Stream velocity

In this activity you will work with an artificial stream. As you change its slope, you will measure the changes in velocity (speed). You will need an open trough (preferably about 1.5 meters or more long and about 5 centimeters wide), a pail or jug, flat cake pans or similar containers, flexible $\frac{1}{2}$-cm rubber hose for use as a siphon, a watch with a second hand (or a stop- (1) watch), a cork, a ruler, and graph paper. Set up the apparatus as shown in Figure 8.9, propping up the trough with boxes or pans. Have enough props so you can change the elevation of the upper end by a total of about 30 centimeters.

First, set the slope at a low angle. Calculate the percent of slope by measuring the *horizontal* distance from one end of the trough to the other. Divide this *into* the vertical difference in elevation between the two ends of the trough. Start a flow of water and drop a piece of cork into the upper end. The cork must be small enough so it doesn't drag on the bottom. Time at least 3 runs and average them. (Have someone keep the pail or jug filled with about the same amount of water during all the runs. Why?)

Calculate the velocity of the stream in centimeters per second. Set the slope at a significantly higher angle and repeat the measurements of time, slope, and velocity. Finally, set the slope at a still higher angle and repeat the measurements.

You now have 3 velocity values at 3 different slopes. Plot them on a graph and connect the points. From this graph, predict different velocities at different slopes. Adjust the slope to a new value and see if your prediction from the graph can be verified by actual measurements. In this activity, you have neglected several variables that have an effect on your measurements. Can you name some? (2)

The erosion cycle. The histories of both river valleys and landscapes can be described in terms of an **erosion cycle**. Just as humans have stages of youth, maturity, and old age, so do river valleys and landscapes (Figure 8.10). These are just relative stages, and years cannot be assigned to them. The (3) erosion cycle is an idealized concept, but it is an aid to understanding erosional history.

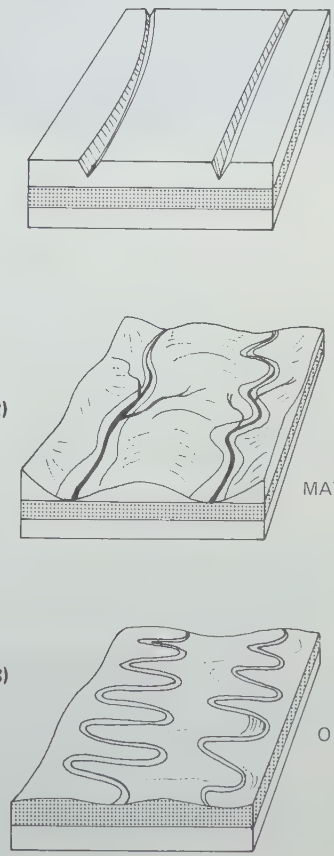
In youth, most of the land is fairly flat with only a few fast streams cutting down through. The youthful river valleys are narrow and V-shaped (Figure 8.1). In maturity, the land

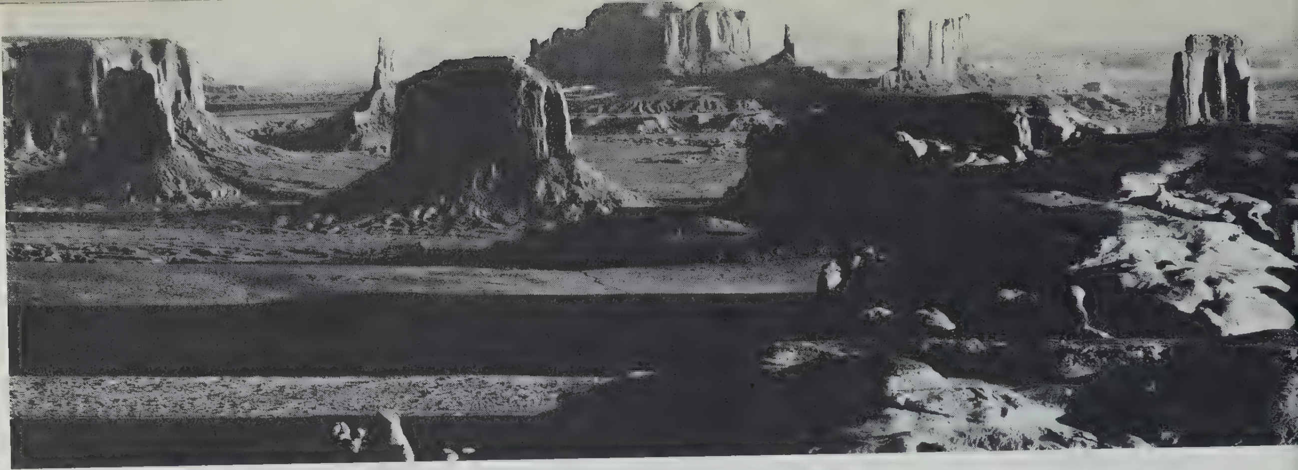
(1) A direct supply of water from a faucet via a basin works better, but commonly a faucet is not available in the right place. The longer the trough, the more accurate the measurements will be; in a short trough, things may happen too quickly to time precisely.

(2) Variables will include velocity of water (due to variation of level in the reservoir), errors in timing, and cork dragging.

(3) The ages of river valleys and the surrounding landscape need not always agree. This is especially true in early maturity where river valleys are commonly youthful.

Figure 8.10 These models are idealized. In nature, streams of an area are seldom spaced quite like this. Bedrock structure and other factors together determine the pattern of stream flow.





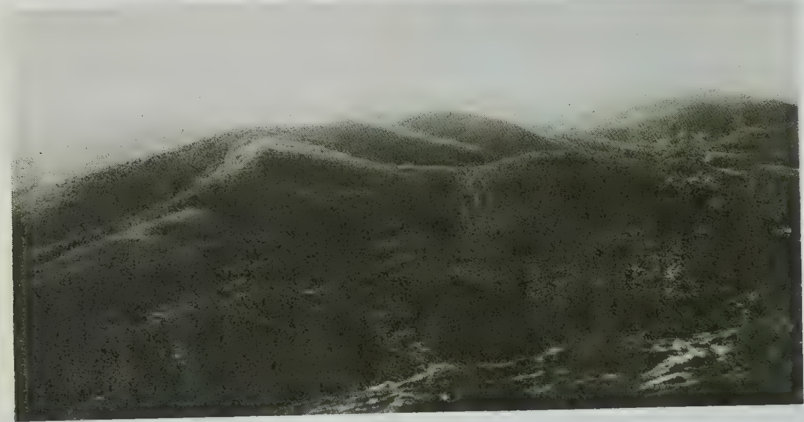


Figure 8.11 (above) Monument Valley in Utah.

Figure 8.12 (left) Hills in the Blue Ridge region of North Carolina.

consists mostly of slopes or hills. The rivers are eroding sideways as well as down, and the valleys are wider. Finally, all the land between the river valleys is eroded, there are no obvious valleys left, and the rivers curve over a low plain. Old age has come. If this old-age landscape were uplifted, the rivers would have a new slope to run down and the cycle would begin again. (In what stages of the erosion cycle are the areas shown in Figures 8.11 and 8.12?)

activity 8.2 Stream erosion and deposition

In this activity, you will study stream erosion and deposition. You will need much of the equipment used in activity 8.1; sediment composed of a mixture of clay, silt, and sand; and modeling clay. Set up the apparatus as for activity 8.1. (You(1) may need another siphon hose to empty some water from the cake pan.) Place a layer of sediment about 2 centimeters deep over the length of the trough. Start the water flow at the upper

(1) You might try this yourself before the students do it. A wide cookie pan with half-inch (1-cm) high edges works well in making an *alluvial fan* because we don't want the fan to form in water. A deeper pan is best for making a delta, which can then build up out of the water. Students should be able to observe many processes: sediment movement, sorting, and deposition. Tell them to *be observant!*

end of the trough, fast enough to move the sediment down the trough. Watch the erosion along the "stream channel." Vary the water flow and observe the relationships of the rate of erosion and the size of the largest particles moved.

At the lower end of the trough, watch the deposition of the sediment. For one experiment, start with an empty pan at the lower end. For another, start with water already in the pan. (What natural landforms does each represent?) Where are the coarsest grains deposited? The finest?

Draw cross sections of the two deposits. If you use a glass cake pan at the lower end, you may see actual cross sections of the sediment through the glass walls.

Put more sediment in the trough and build a dam across the trough near its lower end, about half as high as the trough is deep. Observe what happens to the water level at the dam when the water is flowing. What happens to the sediment when it reaches the dam? What must be done to keep a fairly deep lake behind the dam? Do you think this represents a real-life situation?

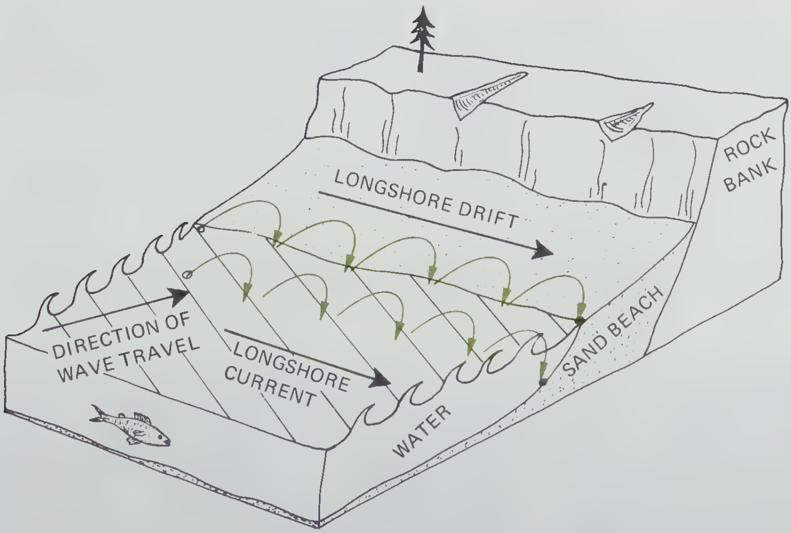


Figure 8.13 Various motions along the shore.

Waves. The most obvious motion in seas and lakes is waves. Waves are caused by winds, and the longer the distance **(2)** of water over which the wind blows, the larger the waves can become. Any drop of water in a wave moves mostly up and down in a circular pattern, but it also moves forward a little bit. A cork bobbing on the surface of wavy water is moving much as a drop of water does within a wave.

(2) Waves are discussed at greater length in Chapters 10 and 11.

If the wave motion can reach bottom, the water will move particles of sediment, and cause erosion of the bottom. Most waves can pick up and move sediment only in shallow water. But they use the sand, gravel, and boulders which they pick up as tools to erode the shorelines. And the waves cause sediment to be moved along the shorelines (Figure 8.13).

CHECK YOUR FACTS (1)

1. What happens to the rain and snow that fall on the ground?

2. What is the water cycle?

3. How do streams carry their cargo of materials?

4. How is a delta formed?

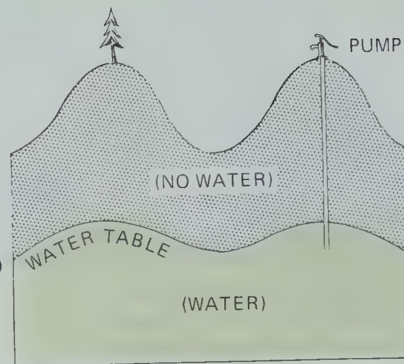


Figure 8.14 The water table.

(1) **ANSWERS** / Check Your Facts

1. Some runs off, some soaks in, and some evaporates.
2. The path of water from the time it falls until it evaporates, condenses, and falls again.
3. As dissolved ions, in fine suspension, and by pushing along large particles and bodies.
4. When the running water of a stream slows down, it deposits its cargo. This cargo eventually builds up into a delta.

GROUND WATER

Ground water is water that is in the ground. Most of man's drinking water, as well as most of the other water he uses, comes from this source. There are great amounts of water underground, and nearly all of it has soaked in from the surface.

Might there be great rivers down there? No, because nearly all underground water is moving through the tiny spaces between sand grains or in other small holes. Underground rivers occur only in caves in limestone areas.

Water wells. Rocks or sediments that have holes or pores are said to be porous. Naturally the holes can hold water. But just because a rock has pores in it, can water flow through it? (What else must also be true?) (2) Wells are drilled or dug down to the depths at which water is present in the pore spaces. The top of this zone of water-filled pores is called the **water table** (Figure 8.14). You already know, from your study of the water cycle, how water gets underground. With that in mind, do you think the water table is always at the same level? (3)

Many people believe that "water-witchers" or "dowsers" (4) can find water with a forked branch of a hazel, willow, or peach tree. Dowsers hold the two ends of the forked branch, with the single end pointing outward and up. When they

(2) Water must be there and the pores must be connected.

(3) The water table varies with the availability of water.

(4) A book entitled *Water Witching, USA* by Evan Z. Vogt and Roy Hyman, (1959, University of Chicago Press, $7.00) is a great source for anecdotes. For example: There were two brothers—one had the "power" and the other didn't, but if the one who did walked behind the other brother, holding the front brother's ears, then the stick worked for him too! The United States Geological Survey, Washington, D.C., has a free pamphlet on water witching (plus dozens of other pamphlets!). Why do witchers find water? Probably because water-bearing layers are so common. But be careful, for this is a touchy and personal subject to many people! Control the discussion firmly.

walk over water, the stick is supposed to be attracted by the water and pulled down. They commonly drill or dig a well at that point, and find water. Scientists can find no explanation for why the branch should be attracted by the water. Yet many people believe in this method. (Do you?) For fun and argument, assume that scientists say that the method can't work. Then try to explain why water-witchers find water with their forked branches.

Erosion and deposition by ground water. Erosion by ground water is a chemical process. As the water moves through sediments and rocks, it dissolves some of the minerals and takes various ions into solution. This makes "hard water." (Ice is hard water, too, but that's different.) All underground water contains ions in solution. So does ocean water, lake water, and river water. Water with relatively few ions in solution is called "soft water." In some places the water is so hard that people have to use water softeners to remove some of the ions.

(5)(5) Calcium ions are the major culprits in most hard waters.

In the study of weathering in Chapter 4, you learned that ground water is commonly acidic because of the dissolved carbonic acid in it. Acidic water easily dissolves limestone. Tiny cracks in limestone can thus be widened into great caves (Figure 8.15). Mammoth Cave, Kentucky, has more than 240 kilometers of explored passages, complete with bats, rats, and blind fish. Caves of one size or another are found in most states.

(6)(6) In November, 1972, cave explorers found a connecting passage from Mammoth Cave into another cave network, making the new network the largest in the world. This news item came too late to be incorporated into the text.

And just as in surface erosion, the eroded material is deposited elsewhere. Calcite, the most easily dissolved common mineral, may be deposited by ground water as cement in sand-

Figure 8.15 Water seeping through the ceiling of this cave deposits on the ceiling some of the calcium carbonate dissolved in it, forming iciclelike objects. Calcium carbonate is also deposited on the floor of the cave by the drops of water.

stones or as cave formations. Or it may reach the surface and be deposited by springs. Or it may finally reach the sea to be deposited as beds of limy sediment that eventually become limestone.

activity 8.3 Porosity

In this activity, you will determine the porosity (amount of holes or pore spaces) in different materials. You will need three 500-milliliter glass beakers, a 100-milliliter graduated cylinder, marbles of average size (enough to fill one beaker to the 300-ml mark), fine lead or copper shot (enough to fill one beaker to about the 150-ml mark), and gravel or sand (enough to fill one beaker to the 300-ml mark).

Carefully fill one beaker to the 300-ml mark with marbles. Pour water from a full 100-ml graduated cylinder into the beaker of marbles, to the 300-ml mark. How much water did you pour in? Now you can easily calculate the percentage of pore space in the "marble material".

Fill a beaker with marbles to the 300-ml mark, and add enough shot *during* the filling process to fill most of the holes between the marbles. Pour water in again. Calculate the percentage of pore space in the "marble plus shot material."

Fill a beaker with gravel or sand to the 300-ml mark. Again add water and calculate the percentage of pore space.

Compare all your numbers. Are there any differences?(1) **What can you say about how the sorting of sediment affects the porosity? What do you think is the greatest percentage of pore space that a rock can have? Would the "sediments" you have just worked with be good ones to drill into for water, gas, or oil? How would the presence of calcite or quartz cement or fine mud in a sandstone affect the porosity?**

(1) The marbles give about the "maximum" for sediment, a perfectly sorted, loosely packed sediment with no cement. (Even mudstones can have a high porosity prior to compaction.)

CHECK YOUR FACTS

(2)

1. Are there great rivers under the ground?
2. Do all sediments or rocks below the surface contain abundant water?
3. How are limestone caves formed?
4. In areas that have porous rocks beneath the surface, would a person have to be very expert to locate a producing water well?

(2) **ANSWERS** / Check Your Facts

1. No, only in limestone caves.
2. No.
3. See page 159.
4. Probably not. Unless some unusual structure is present, it is quite easy to find water in such areas.

GLACIERS

"Ice! Ice! Ice! When are we going to get rid of all this ice?" People in northern North America, northern Europe, and northern Asia may have been saying that as recently as 10,000 or 20,000 years ago. **Glaciers** (moving ice masses) were very important features of that time. Then, ice covered 30 percent of Earth's land surface; today it covers only 10 percent, and most of this is in Antarctica and Greenland. Yet we do live in a geologic age when glaciers are important, and in order to fully understand the erosion of Earth's surface, we must study glaciers.

How do glaciers form? There are two main types of glaciers. **Continental glaciers** cover Antarctica and Greenland today, and **valley glaciers** occur in the mountainous regions of the world. Both types can be seen in Figure 8.16. How on earth do they form?

Glaciers form in areas of heavy snowfall, where more snow falls each year than melts. As the snow becomes thicker, more and more pressure is placed on the underlying snowflakes. They melt at the point where they touch each other, for the pressure is higher there. The water moves to nearby points of lower pressure, and refreezes there as small solid ice crystals. (You do this when you make a snowball with your warm hands.) Thus as more snow accumulates each year, more turns to ice. The ice may eventually become hundreds or thousands of meters thick.

When the ice becomes thick enough, it may begin to move or "flow." This is a result of gravity and the great weight of the pile of snow and ice on the bottom ice. Once the ice is moving, it is a glacier.

Figure 8.16 The valley glacier (the closest part of the picture) is flowing over the top of and down the side of a high rock ridge. The supply of ice for the glacier is coming from the higher continental glacier in the distance.

Movement of glaciers. The ice cap in Antarctica seems to be moving very slowly, but valley glaciers often move a few centimeters to several meters per day. On steep mountain slopes some valley glaciers have moved as much as a hundred meters a day. Friction of the ice on the material beneath affects the speed of glacial movement.

One of the earliest estimates of the rate of glacial movement was made in the Alps. An avalanche thundered down from a high peak onto a valley glacier. It swept three mountain climbers to their deaths, essentially making them a part of the glacier. A scientist predicted that the men would appear at the melting lower end of the glacier in 35 to 40 years. Forty-three years later they showed up, dead.

People commonly think that glaciers act like gigantic bulldozers, pushing and running over everything in front of them. This isn't quite true. Whenever they can, they take the easy path around an obstacle rather than climb over it. And the easiest paths for valley glaciers are existing stream valleys. We know that liquid water flows downhill. Frozen water behaves in much the same way. Even the large con-**(1)** tinental glaciers of the past moved fastest along paths of least resistance. So the advancing fronts of continental glaciers were not straight, high walls of ice. They were uneven, with "tongues" of ice that moved faster down stream

(1) You might emphasize that, as with water, gravity is the underlying controlling factor in the movement of ice.

valleys and other low areas. And the ice, although perhaps a thousand meters thick, wasn't always thick enough to cover everything.

Glaciers continue to advance only as long as the climate is cool enough to prevent too much melting. When the climate warms, glaciers must retreat. Does this mean that they pack up their icebags and head back to a colder climate or back up the mountain to a cooler altitude? No, it simply means that the fronts of the glaciers melt back. The ice within a glacier may continue to move forward, but the glacier is melting at its front end faster than it is moving forward.

Erosion by glaciers. Glaciers are effective agents of erosion, but they aren't as powerful as you might think. You may have heard that the glaciers of the past eroded away the old mountains of Canada and the Lake Superior region. The truth is that they removed the weathered rock and probably only a few tens or hundreds of centimeters of unweathered rock. (Locally, maybe, a little more.) It was our old friend running water, working slowly but surely, that accomplished this task millions of years before the glaciers appeared!

Glaciers easily pick up and carry loose material of all sizes. The particles then serve as tools in the ice, and the bottoms of glaciers act like great sheets of sandpaper. The bedrock, and the tools themselves, become scratched and grooved and even polished.

Valley glaciers with these tools do erode much solid rock. They change the V-shaped mountain stream valleys in which they are moving into broader U-shaped valleys, which are sure signs of a glacial history (Figure 8.17). Each valley glacier starts high in the mountains, where it erodes a basin-shaped depression (Figure 8.18).

Figure 8.17 (below left) The rounded bottom and steep sides of this U-shaped valley are typical of mountain valleys that have been eroded by glaciers in fairly recent times.

Figure 8.18 (below right) Basin-shaped depressions like the one shown are common sights in mountains that have been eroded by glaciers.

Figure 8.19 Unsorted, ice-deposited glacial till can be seen behind this scientist.

Deposition by glaciers. When glaciers are no longer healthy, they slow down, melt back, and drop their heavy loads of sediment. The sediment is either deposited by the ice itself or by the running water from the melting ice. Ice-deposited material is called **glacial till** (Figure 8.19). It is unsorted because, unlike water and wind, glacial ice picks up and drops material varying in size from specks to small houses. However, sediment deposited by meltwater from glaciers will be sorted into layers of finer and coarser grains like any stream-deposited material. Sand and gravel pits in glaciated areas are examples of **meltwater deposits**.

Glaciers that are no longer advancing, but in which the ice is still moving forward, deposit till along their fronts as long ridges called **moraines**. Melting glaciers also drop much of their load beneath them as a layer of ground moraine. Ground moraine in Minnesota is commonly 60 meters thick, and in some areas of central Michigan it is more than 350 meters thick. In Figure 8.20, the dark strips are also moraines deposited along the sides of valley glaciers. Do you think they are unsorted till or sorted sediments?

Special effects of glaciation. The continental glaciers that existed until about 10,000 years ago were responsible for many of the land features that we see today. The depressions now occupied by the Great Lakes were at least partly dug out by the glaciers, and the lakes were much larger when they were dammed by ice and moraines and were filled by the meltwaters. These larger lakes were commonly much deeper than the present lakes. For example, old shorelines of ancestral Lake Superior are now located 150 meters above the present lake level.

Figure 8.20 As the smaller glaciers feed into the larger glacier, the moraines along their sides become strips running down the middle of the larger glacier.

Glacial Lake Agassiz, which covered large parts of Manitoba, Ontario, Minnesota, and North Dakota, was formed by meltwater. It was probably the largest freshwater lake that ever existed on Earth. The countless smaller lakes of Wisconsin, Michigan, Minnesota, Manitoba, and Ontario are also due to glaciers. Most of them were either dug out of bedrock by the glaciers, or they formed in hollows on or behind moraines and other deposits. (Do you know what slogans are printed on the license plates of Minnesota, Michigan, and Manitoba?)

(1)(1) Minnesota—"10,000 Lakes"; Michigan—"Great Lakes State"; Manitoba—"Sunny Manitoba—100,000 Lakes."

Even in the dry southwest of the United States, where the continental glaciers did not reach, glaciation had its effects. Climatic changes due to the presence of glaciers to the north caused so much rainfall that numerous lakes were formed. Most of these have since dried up completely. Great Salt Lake in Utah is one of the few remaining ones; it was once much bigger.

(2)(2) The ancestral body of water, called Lake Bonneville, was more than ten times the size of Great Salt Lake.

Most geologists agree that the great weight of the continental ice sheets caused the underlying crust to be pushed downward. Now, 10,000 years after the glaciers melted, the crust is still rising. The greatest rises are in the Great Lakes-Hudson Bay region and in the Scandinavia-Finland region, where the glaciers were the thickest. In places the rate of uplift is about one meter per century, pretty fast for crustal movements.

Is the Ice Age over? Is there more ice in our future? We know that the glaciers melted back about 10,000 years ago. Geologically speaking, this is just "yesterday," so they could well return "tomorrow"! Although the climate seems to have been warming up for the past 100 years, most geologists believe that glaciers will probably return sometime within the next 100,000 years or so. Some even suggest that they might return in 5,000 years, based on a cooling trend since 1940.

The last advance of ice from the Arctic probably started 70,000 years ago, and the ice has made four major advances and retreats in the last one or two million years. This repetition certainly indicates that glaciers may advance again. Perhaps once, perhaps a dozen times, or perhaps a hundred times! But we can be sure of only this—there will either be more glaciation, less glaciation, or the same amount as at present! Don't lose any sleep over it—you'll be long gone by then!

CHECK YOUR FACTS

1. Where is most glacial ice found today?
2. What are the two main types of glaciers?
3. What happens to a glacier when the climate warms?
4. When did the last advance of ice from the Arctic begin?

(1)(1) ANSWERS / Check Your Facts

1. Antarctica and Greenland.
2. Ice caps or sheets and valley glaciers.
3. They retreat.
4. The last ice age began 70,000 years ago; it ended about 10,000 years ago.

WIND

Winds are far more important to us because of their effect on weather and climate than because of their eroding powers. Only in dry climates are winds important agents of erosion and transportation. Why? Because wet sediment is generally too sticky to be eroded by wind and too heavy to be transported.

Deserts, the result of dry climates, cover about one fourth of Earth's land area. And since there are deserts in the southwestern part of the United States, no study of erosion would be complete without a short section on wind. Most of us think of deserts as vast expanses of **sand dunes**, piles of windblown sand (Figure 8.21). Actually, dunes occur only in parts of some deserts, and furthermore, not all sand dunes are in deserts. The requirements for sand dunes are simply loose, dry sand and strong winds. Small groups of sand dunes are present along many beaches of oceans and lakes.

Figure 8.21 Sand dunes.

Erosion and deposition by wind. Air is only $\frac{1}{800}$ as dense as water, and therefore cannot carry the heavy particles that water can carry. Wind can move faster and can be more turbulent than water, but in spite of this, wind can move only small particles. (We will ignore the rare tornadoes and hurricanes that are capable of moving houses!) Sand grains are rarely lifted more than a meter above the ground, and then are moved only short distances. Clay and other fine particles can be lifted thousands of meters above the ground and transported thousands of kilometers. However, even in desert areas, the running water from a few rainstorms a year probably erodes much more material than wind does.

Dust storms are common, but true sand storms are rare. A long drought occurred in the Great Plains area of Kansas and Oklahoma in 1933, 1934, and 1935. This, together with poor farming methods, allowed winds to blow away much of the fine topsoil. This resulted in the "dirty thirties" and the famous "Dust Bowl" (Figure 4.6). The big dust storms darkened skies along our eastern coast, and even far out to sea!

Much of the fine sediment that settles in the deep oceans far from continents and islands was carried there by wind. And someone has suggested that every square kilometer of Earth's land area probably contains some fine material from every other square kilometer of land on Earth.

CHECK YOUR FACTS

1. In what climates are winds important agents of erosion and transportation?
2. Are all sand dunes in deserts?

(2) (2) **ANSWERS** / Check Your Facts
1. Dry climates.
2. No; some occur along beaches.

MAN AND CHANGE

An agent of erosion that we have barely mentioned is man himself. We are near the bottom of the list in total effectiveness to date, but we've had a rather late start. We are, however, coming on strong. In only a few centuries, we have greatly increased nature's rate of erosion. Bad farming methods, over-grazing of grasslands, and over-cutting of forests have led to increased soil erosion. Much of our land will never again be as fertile as it once was. Much topsoil that took tens

of thousands of years to form has been washed away and stripped of its nutrients in a short time.

We need more land for homes for our growing population. So we "develop" the countryside by subdividing it into small lots and erasing the natural look. We fill in or drain the ugly swamps that, after all, are used only by ducks and muskrats and insects, and the songbirds that feed upon the insects, and the animals that drink the water, and a few dozen other kinds of plants and animals that are links in the food chain. We cut paths through the forests for power lines, very wide so trees can't fall on the wires. And to make sure that trees and brush don't grow there, or along roadsides, we spray with poisonous chemicals. We cut down the big trees, which bring enough income to pay for the bulldozers that make the wide, straight roads. On the homesites, the first step sometimes is to bulldoze down the trees and scrape off all other natural vegetation. This poses no problem, because small shrubs can be planted later, if enough good soil remains after the man-made erosion. And on, and on, and on. . . .

APPLYING WHAT YOU HAVE LEARNED

1. How would the building of more dams along the Grand Canyon of the Colorado River, and elsewhere along its course, affect the rate at which the Colorado River erodes its valley?

2. Which river has the largest drainage basin—the Mississippi or the Amazon? Does this account for the difference in amount of water carried by each?

3. The Mississippi River transports, on the average, close to 200,000,000 kilograms of clay and silt to the Gulf of Mexico each day. How many railroad car loads is this if each car can carry 70,000 kilograms?

4. You learned that the Amazon's daily discharge of water would cover Texas to a depth of about 2.5 centimeters or New Jersey to a depth of about one meter. How deep a layer of water could it deposit over your state in a day? (Hint: use ratios of area and depth).

5. If you were a *spelunker* (one who likes to explore caves) and wanted to find a previously undiscovered cave system, what would be the first information you would need to pick out a good area in which to search?

(1) (1) **ANSWERS** / Applying What You Have Learned

1. The slowed river would cut down more slowly.
2. Another factor is amount of rainfall.
3. Approximately 3,000 carloads. You might ask students to figure how long the train is if each car is 10 meters long (approximately 30,000 meters).
4. The quickest way is to set up a ratio of the area of your state to that of either Texas or New Jersey, and then calculate the ratios of water depth.
5. Limestone (or dolomite) underlying an area.

6. It has been estimated that when the continental glaciers were most widespread, sea level was as much as 135 meters lower than it is today because of all the water tied up as glaciers. From a map of North America and the adjacent continental shelves, figure out where the coastlines of North America would have been. Which present-day seaports would have been high and dry?

7. What would happen to the coastlines of North America if all the present glaciers melted? How much would sea level rise? Figure it out from the following data: Glaciers today cover about 15,500,000 square kilometers; the average ice thickness is close to 1 km; the oceans cover about 360,000,000 square kilometers; ice has a specific gravity of about 0.91 (water expands when it freezes, and when it melts it occupies only .91 of its previous volume). If sea level rose that much, which of our major cities would be under water?

8. In studying the water cycle, you learned that the total amount of water on Earth stays about the same. However, there is probably a small amount of water *added* to the total each year. Where does it come from? Also, a small amount is essentially *removed* each year, and probably doesn't reappear for millions of years. Where does it go?

9. Keeping the friction of glacial ice on solid rock in mind, which part of a valley glacier do you think should move the fastest? Make a sketch.

10. Why might a water well "go dry"? There was an instance where a big factory moved into an area and drilled a deep well. Not too long afterwards, nearby wells at various homes went dry. Why?

6. A world map with ocean depth contour lines would help you here. Such a contour line at 135 m (approximately 75 fathoms) would indicate where that shoreline probably was.
7. Total ice is estimated at 15,500,000 km^3. If this were to become water, the water volume would be 0.91 of 15,500,000 km^3 or 14,105,000 km^3. Dividing the volume by the oceanic area gives an average sea level rise of nearly 40 meters. (This estimate may be low by a factor of 2.)
8. Volcanic activity adds a small amount of "juvenile" water. Some water is "removed" by being trapped between grains of sediment and then buried.
9. The central part (in cross section), away from the bottom and the sides.
10. The water table drops too low because of insufficient rainfall or excessive use. When a well is pumped, a "cone of depression" forms around the well as the water table drops. If it drops too much, shallow wells are left high and dry.

KEY WORDS

leveling (p. 148)
weathering (p. 148)
erosion (p. 148)
deposition (p. 148)
avalanche (p. 149)
landslide (p. 149)
water cycle (p. 150)
sheetwash (p. 151)
drainage basin (p. 151)
delta (p. 152)
alluvial fan (p. 152)
erosion cycle (p. 155)
water table (p. 158)
glacier (p. 161)
continental glacier (p. 162)
valley glacier (p. 162)
glacial till (p. 164)
meltwater deposit (p. 164)
moraine (p. 164)
sand dune (p. 166)

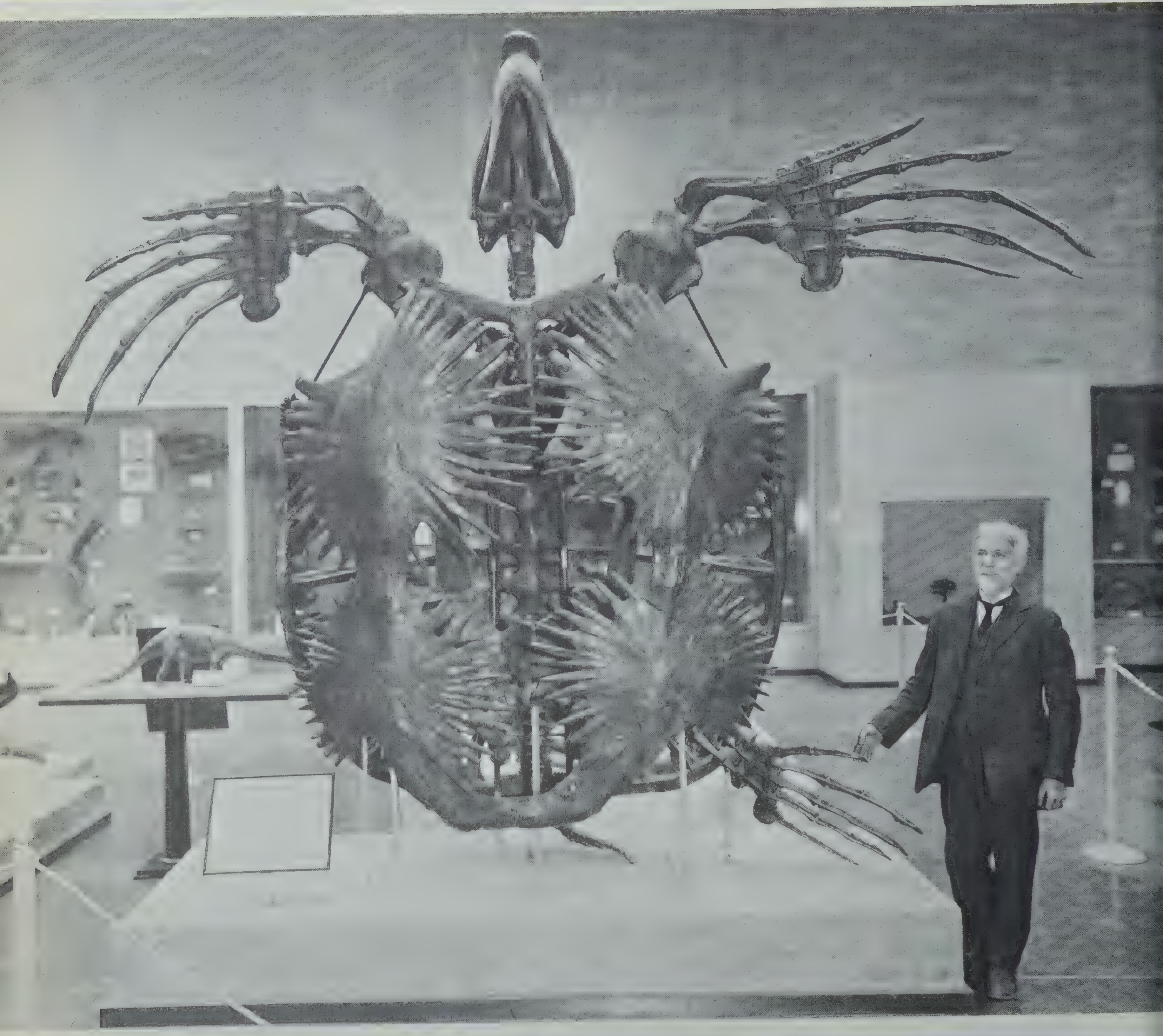


Figure 9.1 About 75 million years ago, this giant turtle swam in a shallow sea over what is now South Dakota.

Introductory Demonstration

Show the class a 35-mm slide of layered sedimentary rocks, preferably horizontal ones. Alternatively, you may show a sample of sedimentary rock with 3 or 4 thin layers. Ask your students to work out a way of telling which layer of rock is the oldest and which is the youngest. See Commentary, page T13.

chapter 9

Change Through Time

If you take a course in the history of civilization, most of what you learn is determined by studying the writings of people who lived during the past. But how do you study geological history —that is, the history of Earth? No one was around when Earth was born. No one was around to record its birth and its long, long history. Obviously, to study geological history, you need something other than written records.

THE RECORD IN THE ROCKS

Sedimentary rocks are the most common rocks exposed on (1) Earth's surface, and they are the most commonly used record of what happened on Earth in the past. Sedimentary rock, as you know from previous chapters, began as sediments. Many sedimentary rocks are folded and tilted, but the folding and tilting happened *after* the sediments were deposited. The sediments that formed the rocks shown in Figure 7.1 could not have been deposited that way, could they?

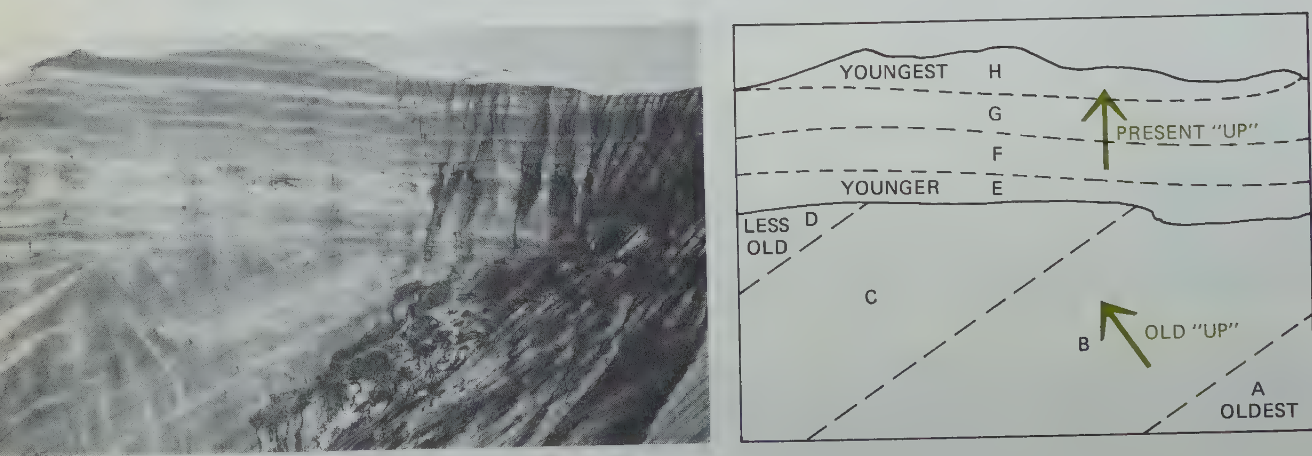
(1) Under the loose material such as soil, about 75% of Earth's land has sedimentary rock at the surface. Of the rest, about 15% is granite and 3% basalt. In many states, for example, in Kansas, it's very difficult to find an igneous rock other than a boulder carried in from elsewhere. Information concerning a geological map of your state can be obtained from your State Geological Survey or from: Map Information Office, U.S. Geological Survey, Washington, D.C.20025.

Principle of superposition. It is a general principle in geology that most sediments are deposited horizontally. For example, the mud being brought by a stream into a lake will settle through the water to form a fairly flat layer on the bottom. A teaspoonful of sugar in a glass of water will do the same thing, and so will sediment in the sea. If sediments are added each day to a lake, today's will lie on top of yesterday's. So we can say that in a pile of sediments, the oldest are at the bottom and the youngest are on top. If these particles of sediment become compressed by the weight of the ones on top of them, or if other physical and chemical actions occur, they will stick together and become sedimentary rocks. Even if they later get folded and tilted so they are no longer lying flat, they normally do not change position *in relation to each other*. As long as the earth scientist can tell which way was "up" in the past, he can use the idea that any sedimentary rock farther up in the pile is younger than the one below it. This is called the **principle of superposition** (Figure 9.2).

(1) (1) By looking at the photo in Figure 9.2 several ideas about the history of the area can be deduced. A period of mountain building occurred, during which rocks A-D were folded and uplifted. They were then eroded while above sea level, producing the irregular contact between the sequences A-D and E-H. The sea then covered the eroded surface, rocks E through H were deposited and another uplift occurred. Another erosion surface is what one sees now in the photo.

Correlation of rocks. The principle of superposition tells us which layers are older and which layers are younger in a rock formation. But what if we are studying two rock formations far apart from each other? One step in finding out the geological history of an area is to compare the rocks in different parts of the area and try to match them according to age. This matching process is called **correlation**. Rocks in one

Figure 9.2 The principle of superposition tells us that the sediments were deposited in the alphabetical order shown. Uplift, tilting, and erosion occurred before rocks E through H were deposited.



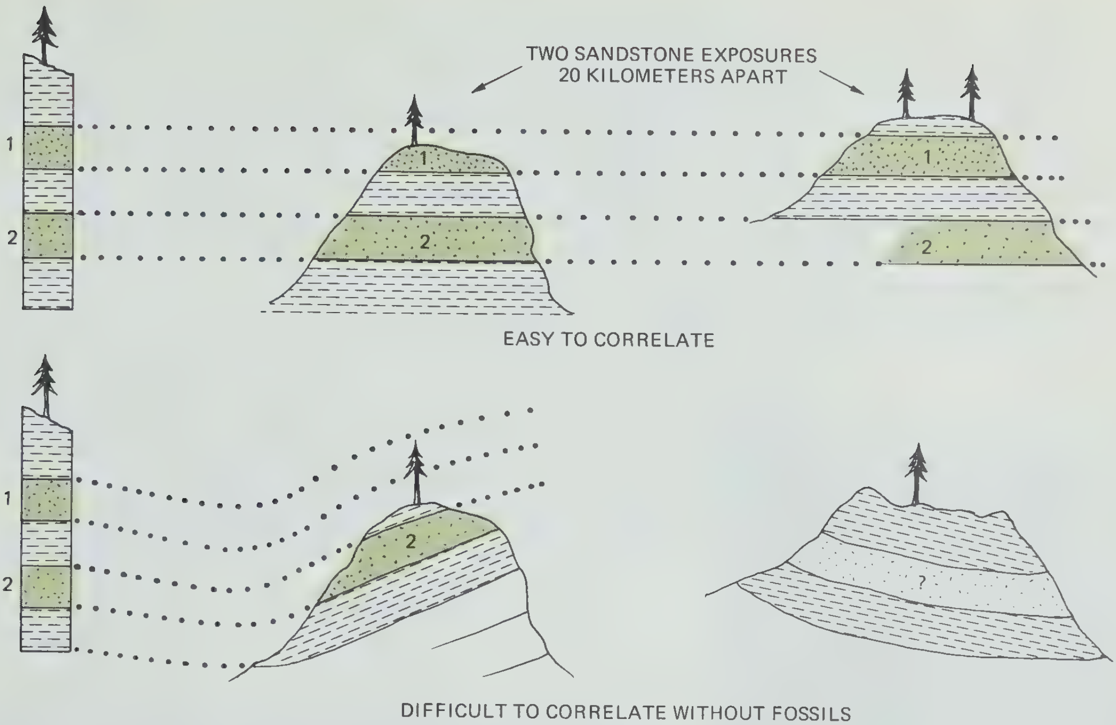


Figure 9.3 The layers with dots in them are sandstones. In the upper diagram, it is easy to see that sandstone 1 in the middle is the same as the upper sandstone on the right. After folding has happened (lower diagram), how can you tell if the sandstone on the right is 1 or 2?

area, for example Illinois, may be compared to those of another area, for example Iowa. If you found a sandstone exposed in Illinois and one exposed in Iowa, how could you determine if they are from the same sandstone bed? As you have seen from your study of uniformitarianism, the processes that formed sandstones millions of years ago were the same processes that formed them thousands of years ago, and that are forming them today. So we can't really tell if the two sandstones are of the same or of different ages. To correlate the two sandstones, we must match them according to their position in the total pile of rocks in the area. And if we find fossils in the sandstones, the fossils will make the job of correlation much easier (Figure 9.3).

Even if the sandstones in Illinois and Iowa were tilted, we could still determine "up" and then study the layers of sedimentary rocks "below" and "above" them. Once these relations are known, we can then try to correlate the two. If they did correlate, we would know they were of the same age. However, we still could not tell what that age was in years, unless more information was available.

Sometimes correlation can be very difficult, even over a relatively small area. For example, rocks deposited at the same time in the same body of water are often not the same kind of rock. As a person wades out into a lake, he may begin walking on sand, but often, before he gets over his head, he feels mud. In the seas that covered most of the United States in the past sands may have been accumulating near the shore, while farther out to sea muds may have been accumulating. So the correct *time* match would be between a sandstone and a shale. If the sea that once covered what is now Illinois was shallow while the same sea to the west in Kansas was deeper,

Figure 9.4 Various fossils are shown in these photographs. At left is a fossil *brachiopod*. The form of the brachiopod shell was preserved by sea bottom mud many millions of years ago. At the lower left is a horsetail plant. The plant decayed, but the carbon in it remains as a thin black film on the rock. Shown below are fossil dinosaur bones.

the Illinois rocks might be sandier than those of the same age found in Kansas. Perhaps we would find a beach deposit with ripple marks still farther east. All could be of the same age, but they would be different rocks formed in different environments. The rocks may also have different thicknesses. In our example, the sand may have been deposited faster and may be one meter thick after 1000 years, while the mud to the west may be only five centimeters thick after 1000 years.

Fossils. The fossil remains of once-living animals and plants are often found in sedimentary rocks, especially shales and limestones (Figure 9.4). When an animal or plant dies and is buried, it may be preserved, especially if it has hard parts such as shells or bones. Of the animals that lived at any one time, very few are preserved. Animals that live in water have the best chance of being fossilized. Particles of mud or lime that settle to the bottom may cover them, and if the water is still, it will not break up the hard parts. Animals and plants that lived on land are fossilized less often. For example, today you can often dig down in the mud of lakes or oceans and find shells. If the mud hardens, as more mud depositing on top pushes down and changes it to rock, the shells will remain. But if you dig down into the soil of Wyoming, where millions of buffalos were living and dying for thousands of years before Europeans came to this country, you would not find many bones. Coyotes and other animals gnawed the bones, rains washed them away, and only a few were buried rapidly enough to be preserved.

There are other less common ways to preserve things. The woolly mammoth, a type of elephant, lived in cold regions and has been found preserved in glacier ice. The animals were preserved in ice somewhat as we preserve pork chops in a deep freeze. Oil-seeps on Earth's surface can also help preserve plants and animals. If an animal falls into one of these that is of thick heavy oil, or "tar," its skeleton stands a good chance of being preserved. The famous La Brea tar pits in California have yielded many excellent fossils.

(1)(1) When one of these mammoths was discovered in Siberia many years ago it had been frozen for thousands of years. Nevertheless, when it was exposed to the air the smell was so bad the discoverers had to breathe through perfumed handkerchiefs.

For many centuries, men noticed that one group of fossils in a layer of rock could be very different from the group in another layer only a meter or so above or below. Some believed that each group in a lower (or older) layer was destroyed by some catastrophe and the next higher (or younger) group sprang up independently. However, as more and more rocks and their fossils were studied, scientists began to see that

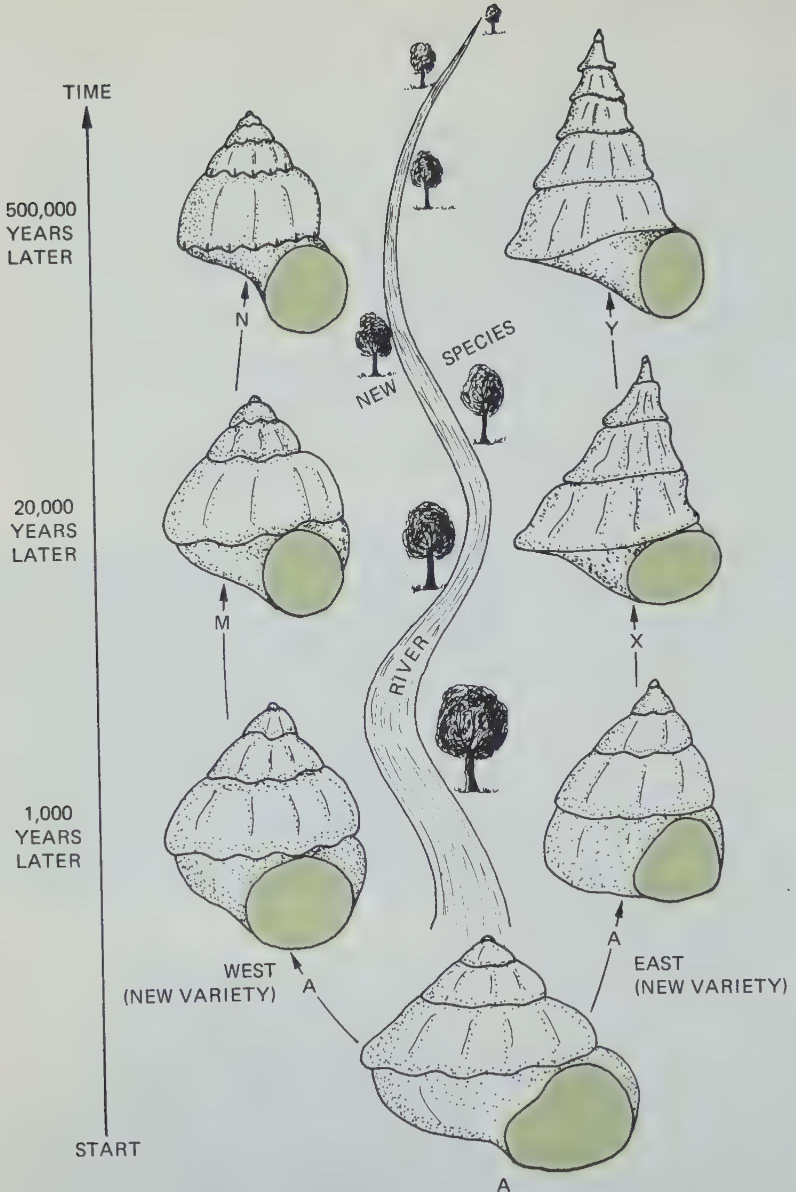


Figure 9.5 Suppose that snail A is a typical individual from a population of snails that lived some time in the past, and suppose that a river (or some other geographical barrier) developed, splitting the population into two groups. Each group kept changing. After 1000 years, two *varieties* could be detected, "A West" and "A East." If some "A East" snails were carried over to the west side, they could get together with "A West" snails and have snail babies. After a much longer separation, say 20,000 years, "A West" and "A East" no longer exist. They have changed into two very different populations, M and X. An M snail and an X snail could *not* produce babies. Each could breed only with members of its own population. M and X are no longer varieties of A, but new *species*. A long time later, M has changed to N and X has changed to Y. Change never stops.

fossils from one layer did not *always* differ very much from fossils in the layers above and below. The fossils in the different layers, though separated in time, seemed to be related. Eventually men came to accept the idea that populations of animals and plants change gradually over periods of time. New, different populations do not just spring up independently. Figure 9.5 shows how one population of snails (A) can change so much that eventually two entirely different populations (N and Y) are produced.

(1) It is interesting to speculate about what would happen if all international travel stopped for a few million years. If the United States were cut off from the rest of the world, would we and our dogs, cats, and other animals all have changed into species different from those of the rest of the world? A discussion of what changes could occur in humans that would make us "better" usually gets lively. For example, if we changed in such a way that human life span averaged 300 years, society would probably have us spending 100 years in **(1)** school.

Now do you see why fossils are so useful in correlating rocks? They are useful because animals and plant populations are *always changing*. Thus, if we find a group of fossils in rocks in Texas and the same kind of fossils, or a very similar kind, in rocks in Montana, the two rocks are of approximately the same age. We say "approximately" because it takes thousands or even millions of years before a population changes enough to produce a visible difference.

activity 9.1 *Using fossils to relate rocks*

Rocks that contain few or no fossils are difficult to match in age. It is much more certain that two rocks are related if more than one kind of fossils can be used to match them. Figure 9.6 shows five groups of common fossils. Each group was found in rock layers many kilometers apart in different states. Group A is from the uppermost, or youngest, layer. See if you can fit the groups into the proper age order.

By the method you have just used, geologists can arrange rocks in order. The principle of superposition and the idea that populations of living things were always changing allow us to "fit" rocks together and put them in order according to age. However, we still don't know their actual ages in years. We only know their relative ages (that is, we know that one rock is older or younger than some other rock.) To find out their *actual* ages, we need something else. We need some kind of "Earth clock."

CHECK YOUR FACTS

1. What is the principle of superposition?
2. How were fossils formed?
3. How do fossils help geologists to correlate rocks?
4. Why must rocks that contain the same fossil fauna (all animals of a particular time or place) be of about the same age?

(2) The sequence is A (youngest) D, B, E, and C (oldest). Some fossils, such as the second from the left in group A, are almost useless for correlation since they represent organisms which have existed without significant visible changes for
(2) very long periods of time.

(3) **ANSWERS** / Check Your Facts

1. That, in any pile of sedimentary rocks, the youngest is on top.
2. Fossils form most commonly by preservation of the hard parts of an organism after burial. The hard parts may dissolve and be simultaneously replaced by minerals. Alternatively, they may dissolve and the cavity remaining will later be filled with a mineral. Bones and wood are commonly preserved if their pores get filled with minerals.
3. Fossils are useful in correlating rocks because organisms are always changing; fossils in a bed of rock represent a short moment in the continuity of change. Normally, the sedimentary rock-forming processes have not changed. The same processes that formed shale or sandstone
(3) 500 million years ago also formed such rocks 10 million years ago, and the rocks may not be very different.
4. Change in organisms through time is not a reversible process; it never leads to a repetition of the same life form. If large reptiles were to become prominent on Earth again, we might accurately call them dinosaurs, but they would never be exactly the same as those that lived before.

MEASURING TIME

A few centuries ago our planet was considered to be only a (1) few thousand years old. This made it very difficult for earth scientists to explain some things. Fossil sea shells different from those living today were found in rocks thousands of kilometers from the present oceans and sometimes in the rock layers of high mountains. If the fossils were once animals living in a sea, and the sediments accumulated over them and eventually became rock, and the rocks were pushed up to form mountains, then a few thousand years seems much too small a number for the age of Earth. Much more time seems to have been needed for all this to have happened. If all this took place in a few thousand years, Earth must have been a violent planet. But some scientists didn't believe the Earth was so young. These were the scientists who believed that things changed gradually over periods of time. They maintained that neither the rocks nor the delicate fossils within them looked as if rapid and violent changes had occurred. They said things happened more slowly, not so very much differently from now. But they needed time if they were to be believed.

(1) In the 1600s some of the accepted ideas on the age of Earth were the product of biblical scholars. By studying genealogies in the Old Testament they derived several dates for the creation of Adam and Eve. One such date, 4004 B.C. in October, was proposed by an archbishop. Most of these estimates fell around that date, so Earth was thought to be about 6,000 years old.

An early estimate of time—the cooling Earth. Sun's heat supplies most of the warmth necessary to support life on Earth, but Earth also has some heat of its own. You have already learned how Earth's temperature increases as you go deeper into Earth. Not very long ago scientists believed that this heat inside Earth was left over from the time when Earth was a mass of molten material. Let us imagine this example to explain the old idea about Earth heat: If you heated a cannonball to its melting temperature and then let it cool in the air, the surface would cool first. Inside the cannonball it would still be hot, even when you could touch the outside without blistering your finger.

If Earth's heat was due to such a simple cooling-off process from its once-molten state, the rate of cooling could be used to get Earth's age. It was thought that if we could measure the total amount of Earth heat being lost to space every year, we could calculate how long this must have been going on to allow Earth to cool from a molten mass to a body with the present surface temperature.

Several physicists made this calculation in the 19th century; the calculations indicated that Earth had been molten about 20 to 50 million years ago. This gave the geologists

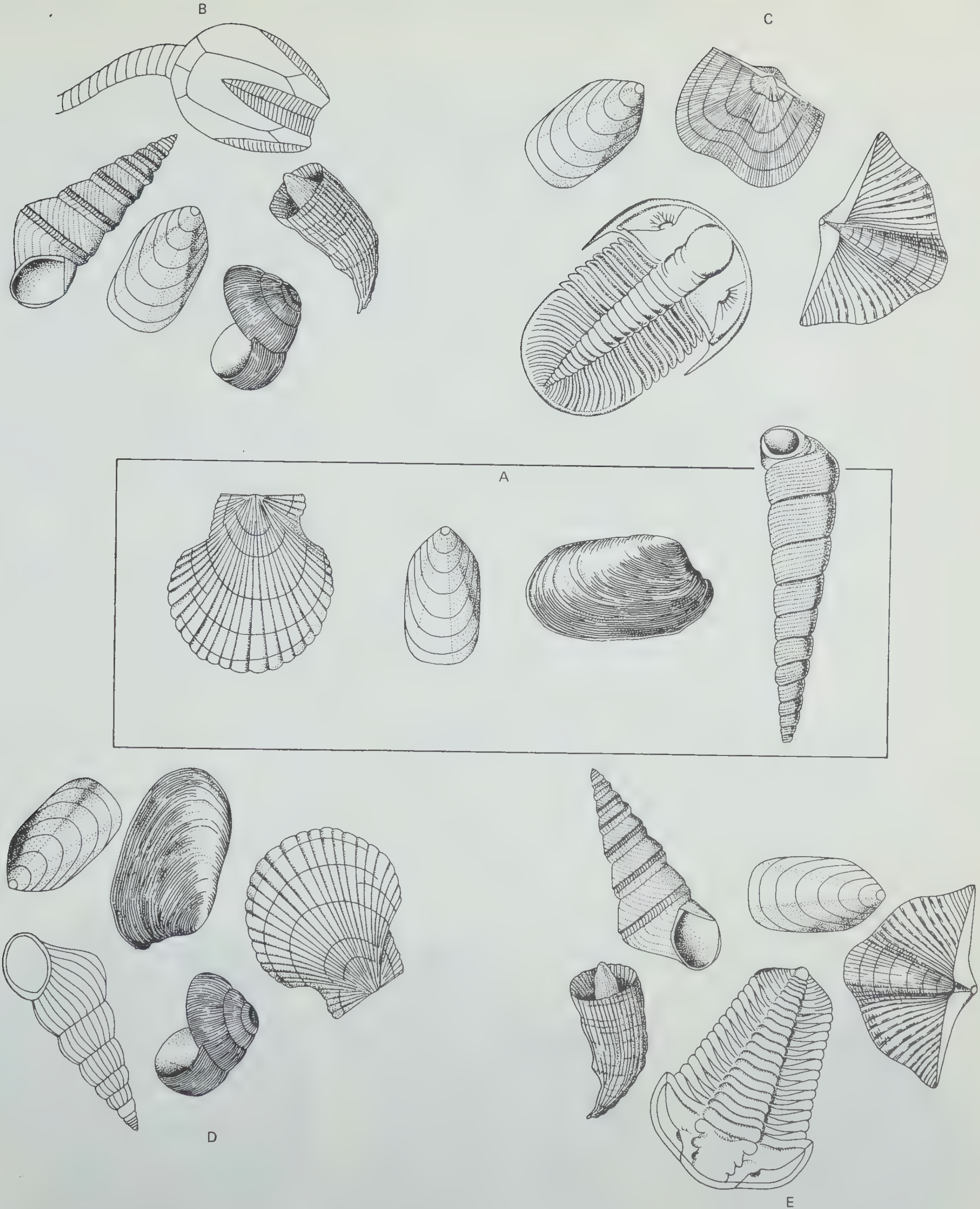


Figure 9.6 Each group of fossils was found in a layer of rock many kilometers away from where the other groups were found. Correlate the rocks according to their age, youngest to oldest, by using the fossils found in them. The group from rock A is the youngest.

much more time to use in explaining the origin of Earth features, but also created new problems. Earth must have been still fairly hot not too many millions of years ago, so animals and plants could not have existed for very long. The paleontologists (scientists who study ancient forms of life) were quite disturbed about this, but neither they nor the geologists could find good arguments against the results of the physicists; (1) numbers are so hard to argue with. Tens of millions of years is better than a few thousand, but the earth scientists needed more. (2)

Estimates based on fossils. If animals and plants changed through time, a *great deal* of time seems to have been needed to account for all the different fossils found. The changes were thought to occur slowly in most cases, and some estimates of the rate were made. Of course the time for one group to change noticeably may not be the same as for another group. For example, the fossils of one kind of snail may not show any noticeable change during 5 million years; yet another kind of snail may have changed so much that when you look at one group of these fossils, you might have trouble figuring out who their ancestors were 5 million years before. Figure 9.7 shows some examples of different rates of change. The fossil foraminifera from about 100 million years ago look almost identical to modern ones. The fossil shell of the ammonite from about 150 million years ago does not look much like a modern relative, the squid. Of its modern relatives, only the nautilus of the Pacific has a hard outside shell.

(1) The molten Earth idea in the 18th century resulted in estimates of Earth's age at only 75,000 years.

(2) Another idea which failed proposed the measurement of the amount of sodium in the sea. This part of the dissolved salt, NaCl, is contributed by rivers bringing the dissolved products of weathered rocks to the seas. People thought that if they could measure the total amount of sodium in the sea and then find out how much the rivers added each year, simple mathematics would tell them how long the process had been occurring.

About 75 years ago this was done, and the age of Earth was estimated at 90 million years. This was not a bad guess compared with earlier attempts, but the gross underestimate resulted from not accounting for all the Na in salt deposits, the large amounts of river flow now versus smaller amounts through much of time, and so on.

Figure 9.7 (below) At left is a photograph of a *foraminifera* shell from about 100 million years ago. The shell is about the size of a pin head; a one-celled animal lived inside. It floated about in a sea over what is now South Dakota. It died, sank to the bottom, and was buried and preserved. In the middle is a foraminifera shell netted from a modern sea. Things haven't changed much in 100 million years! At right is a fossil *ammonite* shell of about 150 million years ago. It does not look like most of its modern relatives. Things have changed a lot.

The reasons why different groups change at different rates are complex and not all are known. However, half the fun of science is in thinking about such things and making educated guesses. The important thing to realize is that change is always going on.

Some early estimates based on fossil changes indicated that certain rocks with fossils had been deposited over 200 million years ago. And these were not the oldest rocks. But no one was able to *prove* that the rocks were that old; they could only say that they thought so. The "Earth clock" still had not been found.

Radioactive decay, the "Earth clock." At about the beginning of this century, it was discovered that a piece of uranium ore would expose a piece of photographic film in the dark. Instead of light rays exposing the film, as in a camera, there were other, invisible rays coming from the uranium. Some forms, or **isotopes**, of certain elements emit these rays along with atomic particles. Such isotopes are said to be **radioactive**. (Isotopes of an element are atoms of that element that have different weights because they have different numbers of neutrons in their nuclei.) As radioactive isotopes give off the rays and particles, two other things happen. They change into other isotopes, and they give off heat. For example, one isotope of uranium changes to an isotope of lead, one isotope of carbon changes to an isotope of nitrogen, and one isotope of potassium changes to an isotope of argon.

Today we put radioactive isotopes to many uses. In hospitals we use the emitted rays and particles to kill cancer cells, and in atomic power plants we use the heat energy of the isotopes to produce electricity. To the earth scientist, however, the importance of radioactive isotopes is in their change to other isotopes and in their heating of Earth. The heat given off as they change is now known to be the source of most of Earth's internal heat. So our planet is not just cooling off from a once-molten state. It has, in the radioactive isotopes in rocks, its own heat source! Here is the reason the heat-loss estimate of Earth's age was wrong.

Soon it was found that each radioactive isotope changes to another isotope at a particular rate. To measure this rate, scientists use the time unit called **half-life** (Figure 9.8). One half-life is the time it takes for one half of the original isotope to change to the other isotope. For example, think of a radioactive isotope of element Y that changes to a stable (unchanging) isotope of element Z. By careful measurement, scientists

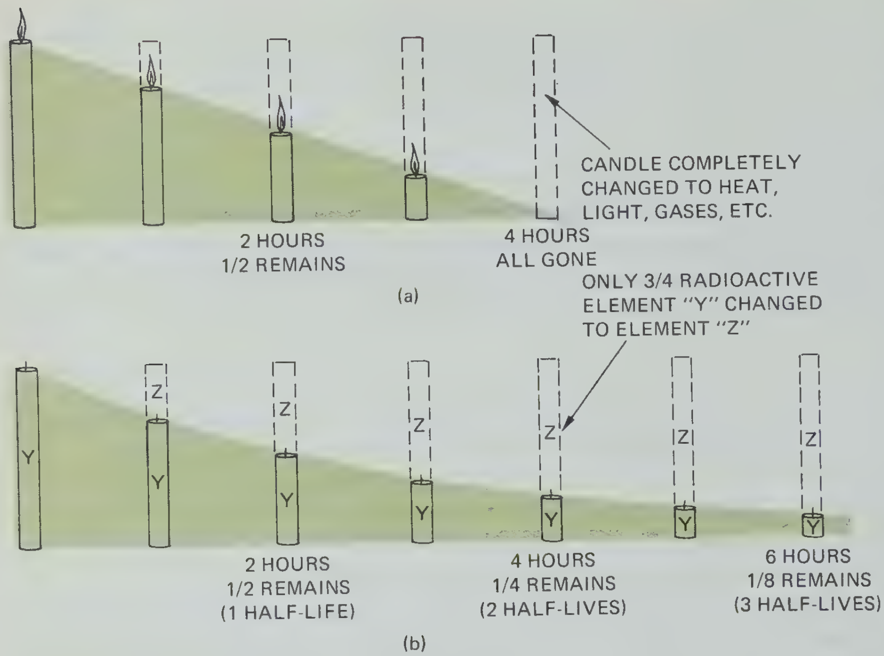


Figure 9.8 Part (a) shows a familiar way things change into other forms. A candle is "decaying," or changing, into light, heat, gases, and so on. If you measured it after two hours and found it half gone, you could truthfully say: "After four hours it will be all gone." Its rate of change forms a straight line going to zero. Part (b) shows how a radioactive element "Y" with a half-life of two hours would decay to element "Z." As with the candle, after two hours it will be half gone. But, instead of nothing remaining after four hours, there still will be one quarter left. Its rate of change forms a curved line, and a long time will pass before the last atom has decayed to element "Z" and the line reaches zero.

have determined Y's half-life to be 100 years. If there was one gram of Y to begin with, after 100 years there would be only half a gram left. The other half has become energy, atomic particles, and element Z. This half gram of Y during the second 100 years would again change by one half, and only one quarter of a gram would be left—a half of a half. How much Y would remain after 300 years?

(1)(1) One-eighth of a gram (one-half of the quarter of a gram left after 200 years).

Here at last is our "Earth clock"! Some radioactive isotopes have a half-life of a fraction of a second; some have a half-life of billions of years. To understand how the age of a rock is measured, let's consider a radioactive isotope of the element rubidium that changes to a stable isotope of the element strontium. Minerals containing rubidium are quite common on Earth. For example, mica often contains a small amount of rubidium. (The rubidium became part of the mica when the mica was formed.) A small amount of mica is all that is needed for modern laboratory instruments to measure the amounts of radioactive rubidium and its offspring strontium. Rubidium changes to strontium with a half-life of 47 billion years. Very slowly indeed. Since the isotope of strontium that we measure in the mica all came from the rubidium, we can know how much rubidium there was in the beginning by adding all the atoms together. For example, if we measured the equivalent

of 400 atoms of radioactive rubidium and 400 atoms of strontium, there must have been 800 atoms of rubidium to start with. Since one half of it had changed, 47 billion years must have passed since the mica was formed. (Of course in samples that have been measured, *far* less than one half of the rubidium has changed to strontium.)

By using this method and other similar methods, earth scientists have dated some rocks as being well over 3 billion years old! By relating these rocks to older ones in which there are no minerals that are good for age measurements, and by measuring the age of meteorites, which come from our solar system, we now have a good idea how old our Earth is: *about* $4\frac{1}{2}$ *billion* years. 4,500,000,000 years, when only 200 years ago men thought Earth was about 6,000 years old! The immense length of time that we now think has passed on Earth makes it much easier for us to try to explain Earth's history.

(2)(2) Our best dates must come from igneous rocks. If we found some rubidium-bearing mica in a sandstone, it would not give us any clue as to the age of the sandstone. The mica may have formed a billion years ago and been weathered out of the old igneous rock and deposited along with sand grains only a few million years ago.

Geologic time scale. Before the "clock" of radioactive change was discovered, earth scientists still needed to arrange the age of rocks in some way. By using the principle of superposition, and by comparing fossils, they were able to divide rocks into groups according to relative age. Trial and error changed this many times. As more was learned about America, it was seen that the same fossils, or at least very similar ones, were here as well as in Europe. Not only were they here, but they first appeared in layers of rock and disappeared in other rocks higher up in the pile in the same sort of pattern as in Europe, England, and other places. From this kind of observation, through the work of many earth scientists, the **geologic time scale** was formed (Table 9.1).

The geologic time scale was worked out by grouping rocks according to relative age. The relative age of a rock is determined chiefly by the fossils it has or does not have. The various groups were given names. Many of the names were chosen from some name relating to the area where the rocks were first studied. An example from the time scale is "Cambrian"; Cambria is the old Roman name for the southwestern part of Britain where these rocks were first studied. If the earth scientist wishes to describe a particular sandstone that occurs just below the lowest rocks with Ordovician fossils, he will use "Cambrian" as part of the description, no matter what part of the world it is found in. This practice allows any scientist in the world to know the age of a rock relative to other rocks. Since the discovery of radioactive dating methods, the actual age in years can be assigned to each group.

Table 9.1 Geological time scale

Era	Period	Biologic events	Years ago*	Time tape**	Geologic events
Cenozoic (Age of Mammals)	Quaternary	first men	2 MY	4 m, 49.8 cm	North America and Eurasia glaciated
					Pacific Coastal Mountains rising
		first manlike fossils	10 MY	4 m, 49 cm	Andes, Alps, and Himalayas rising
	Tertiary		65 MY	4 m, 43.5 cm	U.S. and Canadian Rocky Mountains rising
Mesozoic (Age of Reptiles)		extinction of dinosaurs			
	Cretaceous	first flowering plants			
	Jurassic	first birds			Sierra Nevada rising
		first mammals			
	Triassic	first dinosaurs	225 MY	4 m, 27.5 cm	
Paleozoic (Age of Invertebrates)		extinction of trilobites			Appalachian Mountains rising
	Permian	first reptiles			
	Pennsylvanian	forests of coal-forming plants			
	Mississipian	first large land animals (amphibians)			
	Devonian	first large land plants			Acadian Mountains of Eastern Canada and New England rising
	Silurian	first air-breathing animals (scorpions)			Taconic Mountains of New York and Quebec area rising
	Ordovician	first animals with backbones (fish)			
	Cambrian	trilobites, etc.			
		first common fossils	600 MY	3 m, 90 cm	
		rare animal fossils	1000 MY	3 m, 50 cm	
		first certain fossils of one-celled plants (algae)	2000 MY	2 m, 50 cm	Many mountain ranges formed and worn down
	Precambrian	possible fossil cells found	3000 MY	1 m, 50 cm	
		Life begins?	4500 MY	0	Origin of Earth

*MY = million years

**measurement on time tape if 1 billion years = 1 meter

activity 9.2 *Making a time tape for Earth*

To get a better idea of geologic time, you can make a time tape. Get a piece of paper tape 5 meters long from an adding machine. Let us imagine that each meter is equal to one billion years of time! Draw a line across the tape at the left end to represent the beginning of Earth. From this line measure 2 meters and 50 centimeters and make a mark. That mark is the age of the oldest rocks in which good evidence of life has been found—2 billion years old. In this chapter you will sometimes find a measurement shown like this: [3 m, 26 cm]. This is the number of meters and centimeters on your tape from the *beginning* of Earth time to the event being discussed. From the

same end line, measure 3 meters and 90 centimeters and draw a line across the tape. That line is the beginning of the Paleozoic Era; it is the point at which fossils become common. The whole tape up to that line can be labeled Precambrian. As we study more about Earth time, return to the time tape and add more information. You may want to refer to Table 9.1 too.

CHECK YOUR FACTS

1. What were some early estimates of Earth's age?
2. What is radioactive decay?
3. What is meant by half-life?
4. What is the geologic time scale?

(1)(1) **ANSWERS** / Check Your Facts

1. Less than 6,000 years (October, 4004 B.C.), 75,000 years, 20 million to over 200 million years.
2. It is the change (or decay) that spontaneously occurs in isotopes of some elements; they lose their identity as one element and become another. The change occurs in the nucleus, and the results of this decay are: a new element, heat, and the emission of (usually), a gamma ray and either a beta particle (an electron) or an alpha particle (each composed of 2 neutrons and 2 protons).
3. It is the time required for one-half of any given quantity of atoms of a radioactive element to change to another element.
4. It is a type of calendar of Earth's history.

THE PRECAMBRIAN ERA

The oldest Earth rocks known are from areas called **shields**. Each continent has one of these areas; you can think of them as the "cores" of continents (Figure 9.9). The rocks of shields are mostly igneous and metamorphic. The oldest Earth rock yet dated by its radioactive clock is about $3\frac{1}{2}$ billion years old. So, for the first billion years of Earth history, we have no rock record. These earliest rocks were probably remelted; this allowed some or all of the elements produced by radioactive decay to escape, and the "clock" was therefore set back to zero. Or maybe the rocks are still around in their original form, and we just haven't found them yet!

The shield in North America is called the Canadian Shield because most of it is exposed in Canada. In much of the United States, it is covered by younger rocks. Most of the shield rocks are not very different from some younger rocks, but their history is more difficult to understand. There are too few Precambrian fossils to use for correlation. These Precambrian cores of continents were later surrounded and covered over by sediments as the continents gradually built up.

First life. No one knows when the first life formed on Earth. No one is sure what the atmosphere was like then. No one knows if the water which covered parts of the shields in Pre-

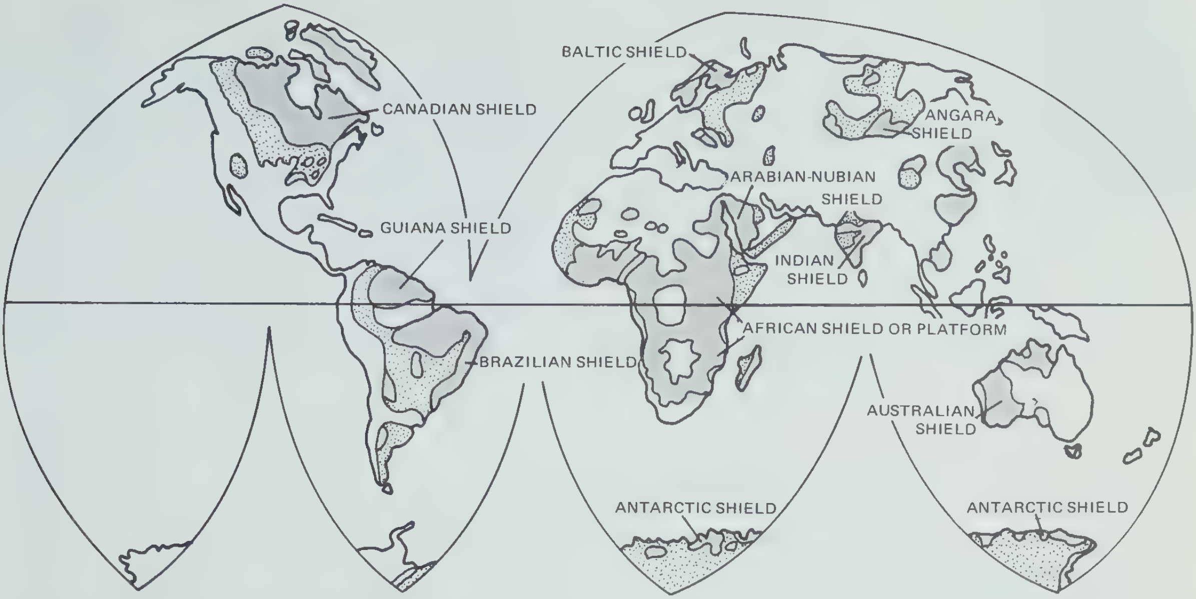


Figure 9.9 The Precambrian shields, shown in grey, are large exposures of very ancient rocks. In the dotted areas, the shield rocks are known to exist but are covered.

cambrian times was salty like modern sea water or not. We do know that the earliest unquestioned life forms found are about 2 billion years old [**2 m, 50 cm**], but fossils have been found that are possibly about 3 billion years old. The most common very old fossils are one-celled plants called *algae*; they are found in sedimentary rocks called *chert.* Chert is finely crystalline quartz, and on the shields occurs in thin layers apparently deposited under water. Often found with the cherts are layers of iron-rich rocks. After the Precambrian era, such extensive beds of chert and iron-rich rocks were never again deposited. Something was happening then that never happened again. Perhaps it was a time when oxygen first became plentiful, and maybe the early one-celled plants produced this oxygen. The appearance of life and iron-rich rocks may be closely related. The steel in your car may be related to the lives of algae billions of years ago! The fossils in the chert may be seen by grinding the rock paper-thin. Light will pass through the thin rock and with a powerful microscope the fossils will appear as brown or black cells. Some cells are round and separate, others are joined together in strings (Figure 9.10).

(2) (2) The atmosphere more than 3 billion years ago almost certainly did not contain much free oxygen, nothing like our present 21%. Some mineral forms in ancient rocks could not have existed in the chemical state in which we find them if free oxygen were abundant. The oxygen in our atmosphere is nearly all derived from the photosynthesis of plants. Some of the very oldest rocks show definite signs of having been deposited as sediments in water. Whether this water was in large lakes or there were large oceans in the early Precambrian is anybody's guess.

(3) (3) Chert is very similar to flint. Arrowheads made of chert are frequently found.

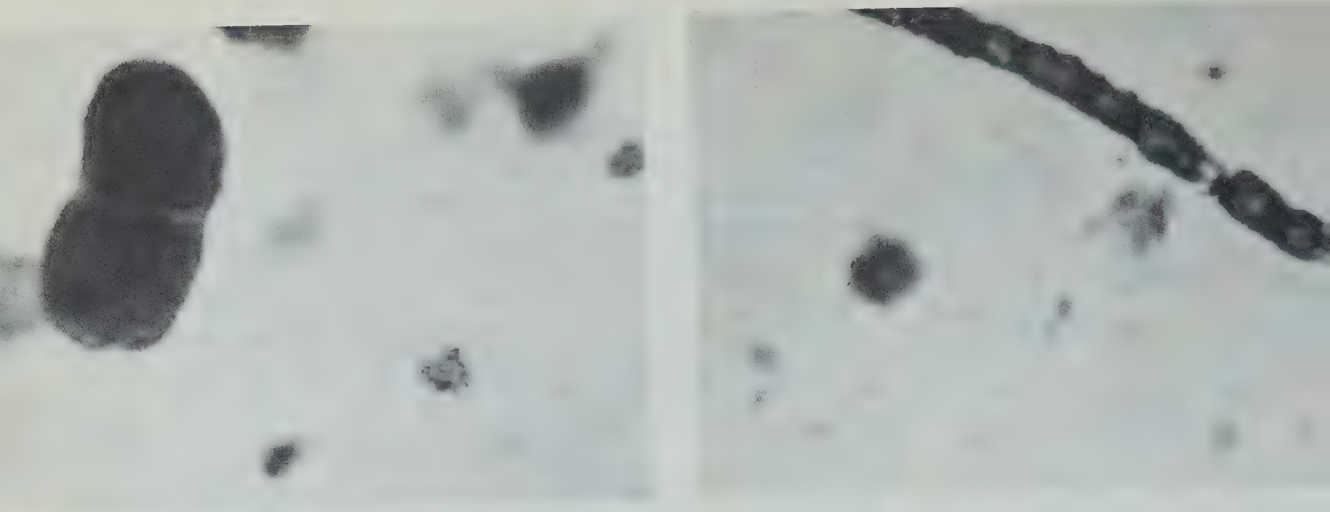


Figure 9.10 These photographs, taken through a microscope, show two types of single-celled plants that lived about two billion years ago. The one on the left is usually seen as a very small sphere, but it was fossilized as it was splitting in two. The one on the right is a chain of single cells. Neither of these forms is very different from some one-celled plants living today.

The oldest fossil *animals* yet found come from Australia. These are known from impressions in sandstone nearly one billion years old [**3 m, 50 cm**]. It seems likely that these animals had no hard parts. Probably that is the reason animal fossils are so rarely found in Precambrian rocks.

CHECK YOUR FACTS

1. What is a shield?
2. How old are the earliest unquestioned life forms?

(1) (1) **ANSWERS** / Check Your Facts

1. The principal areas of exposure of the ancient Precambrian rocks which form the fundamental crustal rock of the continents. In North America, this area includes most of Canada and portions of some of the northern states. To the south there are isolated exposures in the Black Hills, Ozarks, and other places.
2. About 2 billion years old. The best preserved ones are in chert outcroppings along the northern shore of Lake Superior.

THE PALEOZOIC ERA

About 600 million years ago some remarkable things happened. You have already measured the 3 meters and 90 centimeters on your time tape. We are not absolutely sure what happened, but suddenly the rocks have many fossils. Animals with hard shells lived in the seas. These were not all simple animals; some had complicated eyes, many legs, and were often larger than a person's hand. The most common early animals were the **trilobites** (Figure 9.11). Most of the record of the long history of change leading up to all these animals has not been found in the older rocks. This is why we sometimes call the Precambrian the time of "hidden life." What the changes were (in the sea water, in the atmosphere, and so forth) that allowed hard parts to develop, we can only guess.

(2) There was some change in the environment and in the organisms that permitted animals with hard parts to be successful. It is the appearance of hard parts that we are really talking about when we speak of the sudden appearance of fossils. Why were hard parts an advantage? Were they protection, or were hard parts really developed to add weight so an organism could feed on the bottom without expending energy
(2) staying down? All guesses are legitimate.

The seas in which most of these animals lived were not like our modern seas. Modern seas lie mostly in deep basins and are very deep a fairly short distance off shore. The average ocean depth is about 3.8 kilometers. There were probably deep ocean basins in the Paleozoic era too, but deep-water rocks are not often found on what is now land. Most of the rocks in which we find fossils were deposited in shallow seas that covered parts of the continents. Just as life slowly, but continually, changes, so do the positions and levels of ocean basins and continents. A rise in the ocean floors of only a few hundred meters, or a similar lowering of continents, would cause oceans to spread across much of the land. This type of shallow sea is known as a **continental sea**; they have been very common in Earth's history.

For many bottom-living marine animals today, the places with the most food are in shallow water near shore. Shallow water has light. Animals can see better in it, and plants that can be used for food live in it. A shallow sea spread out across a continent greatly extends this type of environmental situation. So animals lived in abundance, and when they died they

Figure 9.11 The trilobites are the earliest common fossil and became extinct at the end of Paleozoic time.

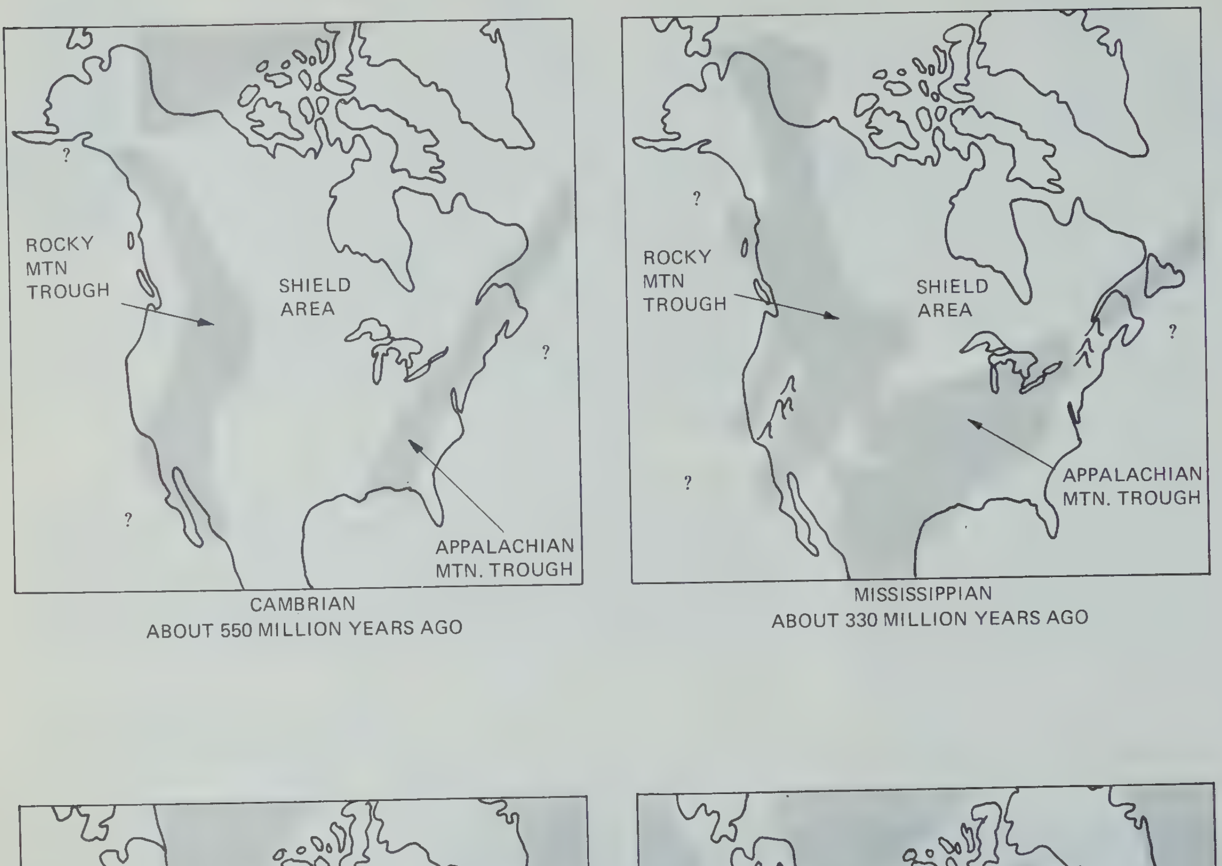


Figure 9.12 Seas over what is now North America are shown in grey. The boundaries of the continent are shown for reference only; they did not exist in the present form at any of the times shown.

were preserved in abundance. Figure 9.12 shows the extent of the seas over North America at four times in the past. As the 350 million years of Paleozoic time progressed, the animals and plants and the seas in which they lived kept changing. By the Ordovician period, many of the major forms of animal life we know today had appeared. It is surprising that lots of modern animals, over 400 million years later, are only variations of the very early types. Of course, many modern forms are far-out variations, but the basic plan is still there. Most abundant in Paleozoic times were animals without backbones, the **invertebrates**. Some Paleozoic invertebrates often found as fossils are shown in Figure 9.13.

Earth's most common animals are still invertebrates. All the fossil ones shown in Figure 9.13 lived under water. Can you think of five land invertebrates? Do you think fossils of (1) land invertebrates would be common in rocks? Why wouldn't they be common?

(1) Land invertebrates commonly known to students are bees, spiders, grasshoppers, beetles, ants, and worms. Cockroaches have been around for about 200 million years, so a few shots of insecticide provide only a temporary cure for their presence. Land invertebrates usually aren't covered by sediments rapidly enough to be preserved, so they are not common fossils. Moreover, terrestrial sediments that are now rock aren't that common anyway. One interesting means of preserving invertebrates is entrapment in amber. Amber is ancient tree resin and many pieces millions of years old have been found with marvelously preserved insects inside.

Early vertebrates. The Paleozoic era is sometimes called "the age of invertebrates." Yet here and there across our Earth, a few fossils of fish have been found in early Paleozoic rocks [**4 m, 4 cm**]. Fish are **vertebrates**, or animals with backbones. (2) The earliest fish seem to have been a jawless, armored type (Figure 9.14).

(2) The lamprey is nearly the sole survivor of the jawless fish which lost their armor long ago. Its lack of jaws is one reason for its life style; it is a parasite on other fish. The appearance of lampreys in the Great Lakes after canals were built to allow shipping from the Atlantic is a good example of the unexpected occurring when man tampers with a natural system. Fishermen lost their livelihood since nearly all the lake trout died, and millions of dollars have been spent in lamprey control. The battle hasn't yet been entirely won.

Figure 9.13 Four hundred million years ago the sea bottom around what is now New York may have looked like this reconstruction. The long-stemmed animals at left are *crinoids*. A large trilobite can be seen near the bottom edge of the picture. The animal with the long straight shell is distantly related to our modern octopus, which swims around nude.

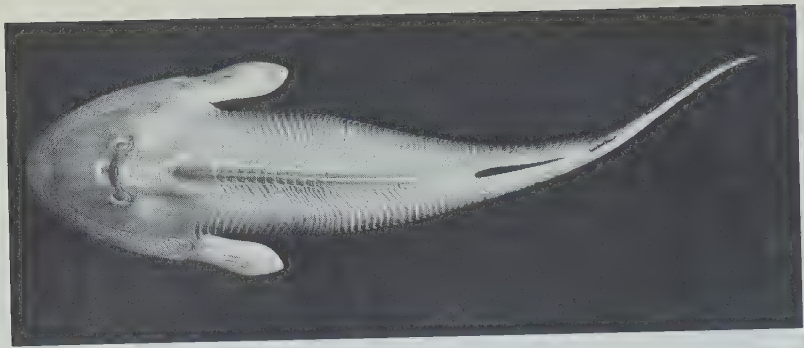


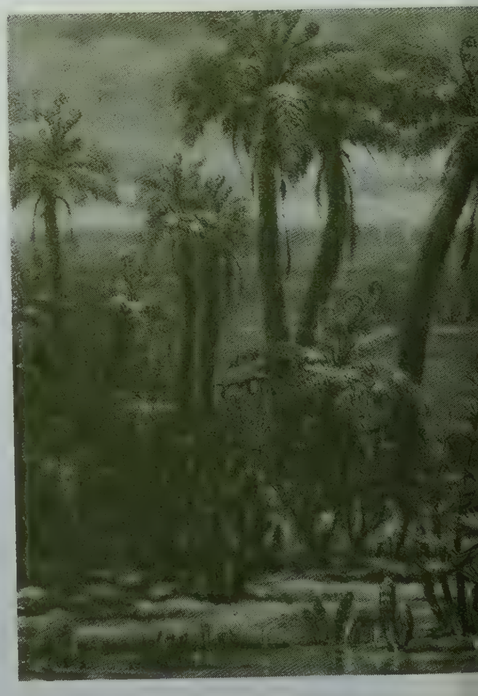
Figure 9.14 This model shows one of the jawless armored fish that represent the earliest known vertebrates. The animal was flattened and its eyes were on top of its head, so it probably lived on the bottom. It is streamlined, but its armor probably prevented it from swimming rapidly. It may have lived where there were strong currents, perhaps in the mouths of rivers.

In the Devonian period, fish were the dominant forms of life on Earth. After fish with jaws appeared, two other types evolved from them. These were the bony fishes and sharks. Sharks have skeletons of cartilage rather than of bone. We usually find only their teeth preserved as fossils. Bony fish, the main type of modern fish, have a hard, bony skeleton, as anyone who has ever swallowed a bone from a trout knows!

How, why, and from what did animals with backbones evolve? What changes occurred over 400 million years ago that led to their appearance? The origin of fish is still a deep mystery. It is an important and interesting mystery, since these first vertebrates are the basic forms that, through long change, finally lead to all vertebrates. They are distantly related to dogs and dinosaurs, pigs and parrots.

Life on the land. Imagine the land surface of the early Earth. Barren. For hundreds of millions of years, through the immense time of the Precambrian, through the early Paleozoic, there were apparently no land animals and no land plants (with the possible exception of some algae). Nothing moved across Earth's land; nothing green blossomed under the sun. What a grim and desolate world it would have seemed, if there had been eyes to see it! Imagine the rapid runoff of rainwater and the erosion of a land with no soil or plants to slow the flow. Some idea of this can be found by seeing what happens today when people ignore our environment. When forests are cut down completely and not replanted, when improper farming wears out the soil and leaves it without plant cover, the land is rapidly washed or blown away.

Near the boundary between Silurian and Devonian time, the first land plants and land animals [**4 m, 10 cm**] appeared. The first land animals had no backbones and the earliest known ones looked something like scorpions. Later in the Paleozoic, insects evolved and these are still the most common land animal. The first vertebrate animals to come out of the



water and crawl on land were fish. The necessary changes in living habits, for both the plants and animals, from life in the sea to life on land are enormous. In the sea, water is always available, sudden changes in temperature are rare, and food is usually readily available. On land, organisms had to change to prevent water loss by evaporation, had to develop new ways to get gases (carbon dioxide and oxygen for plants, oxygen for animals), and had to reproduce differently. Figure 9.15 shows some early plant types; one of the close modern descendents is the horse-tail rush often seen today in swampy areas. Relatives of all the main types of early plants survive today. In a way, Paleozoic plants are often represented today when you turn on the lights in your house. Most of the coal in the United States comes from the compressed remains of Paleozoic plants, and a great deal of the electrical power in our country comes from the burning of this coal. The early land plants developed roots to get water and minerals from the earth and leaves to get energy from the sun. Their reproduction was by means of spores or seeds and pollen, but no flowers and fruit were to appear for many millions of years—honey and sliced peaches were not on the Paleozoic menu.

Figure 9.15 This is an artist's idea of what a forest in the eastern part of what is now the United States looked like over 350 million years ago, during Devonian time. The fern tree on the far right was over 10 meters high.

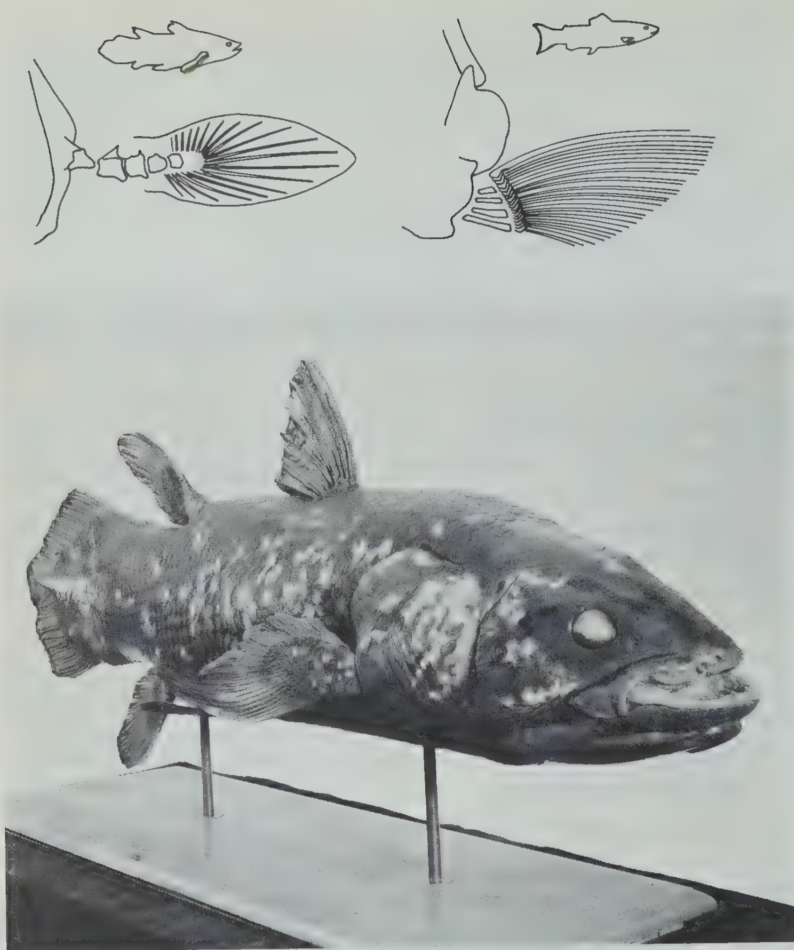


Figure 9.16 The drawing shows the arrangements of fin supports in typical lobe-finned (left) and ray-finned (right) fishes. In the lobe fins, muscles and bones extended into the fin, permitting greater control and flexibility of movement. Such fins developed into the limbs of the land-walking amphibians. The photograph shows a model of a modern lobe-finned fish. Until a fish like this was caught off South africa, this type of lobe-finned fish was thought to have become extinct over 60 million years ago! This "living fossil" has provided us with clues as to how its ancestors were able to change from living in water to living on land in the distant Devonian Period.

From fish to amphibians. Two different kinds of fins are seen on bony Devonian fish fossils. One group of fish developed **ray fins** and these are by far the most common type today. The other had bone and muscle growing down into the fins; such fins are called **lobe fins** (Figure 9.16). Few of these lobe fins are around today. The lung fish of South America, Africa, and Australia are the most common living lobe-finned fish.

Lobe-finned fish were extremely important in the series of changes that led to land vertebrate animals. Both the lobe-finned and the ray-finned fish developed a primitive breathing organ to help them get more oxygen. Many of the ray-finned fish developed in such a way that this organ now functions as a gas-filled swim bladder to help keep them from sinking in the water. In the lobe-finned fish, this primitive lung allowed them to live through dry spells when much of the water in their pond dried up. Since the lobe fins allowed them some crawling

(1)(1) This swim bladder is a common thing to any student who is a fisherman and cleans his own fish. It's usually a clear air-filled bag along the fish's backbone; it helps fish maintain buoyancy.

ability, and their primitive lungs allowed them some direct air breathing, these fish were able to move onto the land and survive for a while. From these fish, as they kept changing over millions of years, came the first vertebrates that were more "land animal" than "water animal." These were the **amphibians**, and they are first known from rocks of late Devonian age [**4 m, 15 cm**]. The lobe fins were now more like legs, and lungs were fully changed to breathe air (Figure 9.17). The early amphibian skeleton is remarkably like that of a fish. Although the amphibians became the dominant land vertebrate animals in late Paleozoic times, today nearly all that remains of the amphibians are frogs, toads, and salamanders. The amphibians were, and still are, caught between two worlds—land and water. Able to live on land, they still generally require moist skin and must go back to the water to breed. Their eggs cannot withstand dryness; nor can they be fertilized out of water. The amphibian's land-water ties can easily be imagined when you see the change from the tadpole swimming in a pond to a frog croaking on the shore. A link between two worlds, the amphibians never succeeded too well in either. Yet they have managed to survive for about 350 million years.

(2)(2) The most familiar salamander is the newt. It's a common pet shop item for terrariums and turtle bowls.

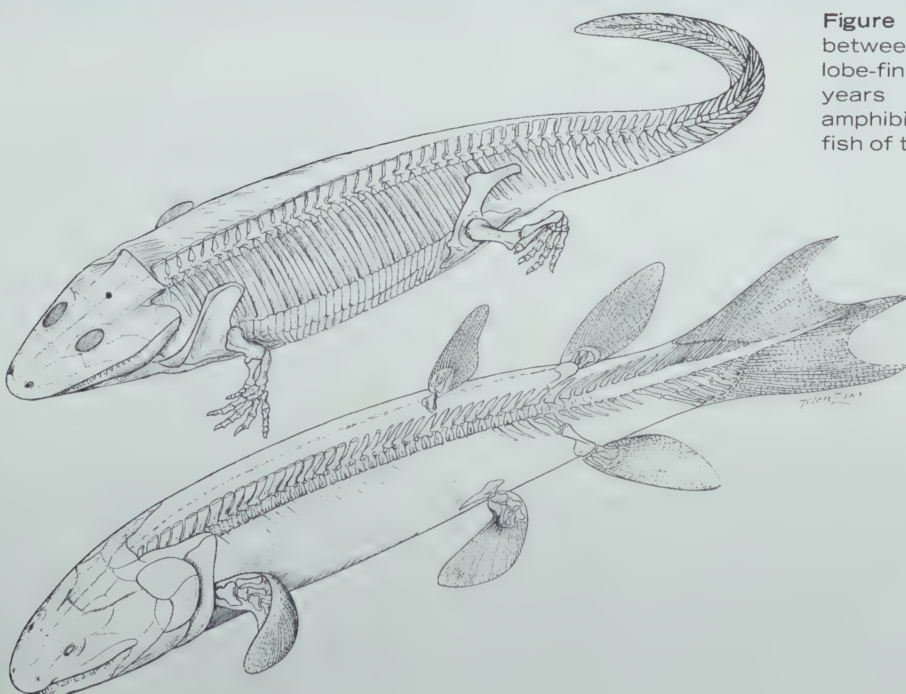
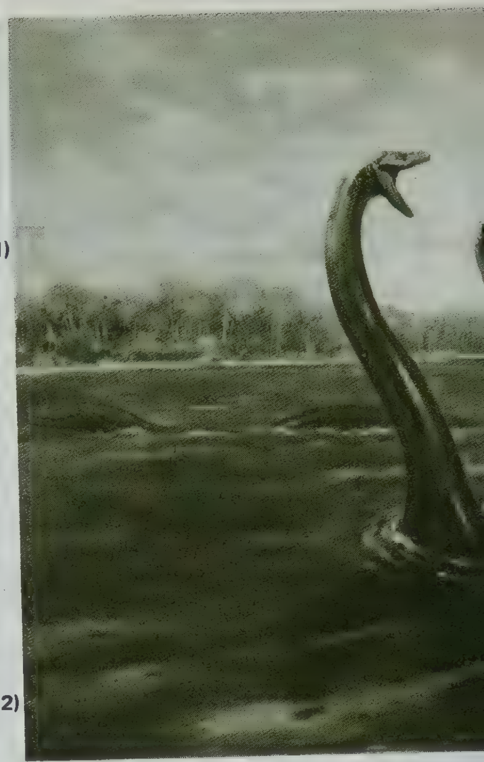


Figure 9.17 Note the similarity between the lower drawing of a lobe-finned fish of 350 million years ago and the primitive amphibian that developed from fish of this type.

Reptiles. The first vertebrates to be completely successful at life on land were the **reptiles**. The changes that took place in each of the millions of generations of amphibians slowly led to the appearance of the reptiles. The main advantage of the reptile was an egg that had a hard shell. Now, the about-to-be-born could grow inside a shell surrounded by life-supporting fluid. Since the egg allowed reptiles to live their whole lives far from large bodies of water, far more of the land could be (1) lived upon. The egg is sort of a canteen for crossing dry lands. So close in skeletal forms are some amphibians to early reptiles that only the presence of eggs would allow us to be certain how to classify the fossil. The first reptiles appear in rocks of Pennsylvanian age [**4 m, 19 cm**].

The Paleozoic ends. The end of Paleozoic time, some 225 million years ago [**4 m, 27.5 cm**], was a time of mountain building in North America. Sediments had been accumulating in a geosyncline along our present eastern coast. The uplift of this geosyncline produced an immense chain of mountains, the Appalachians. Today, some mountains are still rising and the changes leading to new mountains are going on continually. (2) Always there is change. And some changes that took place as the Paleozoic era ended must have been drastic. Many kinds of previously successful animals and plants, both on land and in the sea, became extinct. We know there were changes in climate near the end, but what worldwide events occurred to bring about such broad destruction of life? We don't know—yet.



(1) Reptiles that give live birth still lay eggs, but they are retained inside the female's body. People normally eat only birds' eggs, primarily chickens'. Alligator or turtle eggs also taste very good, but don't get hard when boiled. They taste much like soft-boiled hen's eggs. Reptiles also differ from amphibians by having internal fertilization.

(2) Some coastal mountains in the western United States have risen about one meter in the last hundred years.

CHECK YOUR FACTS (3)

1. When did fossils become common?
2. What is an invertebrate?
3. What is a vertebrate?
4. When did the first vertebrate appear?
5. When did the first land plants and land animals appear?
6. What is the difference between a ray fin and a lobe fin?
7. What is the difference between amphibians and reptiles?
8. What were the first vertebrates to be completely successful on land?

(3) ANSWERS / Check Your Facts

1. At the end of Precambrian time, about 600 million years ago; the beginning of the Cambrian period.
2. An animal without a backbone.
3. An animal with a backbone (even a rudimentary one).
4. The earliest vertebrates known were the jawless fish. They are rare fossils in rocks of Ordovician age, about 450 million years old.
5. Near the boundary between the Silurian and Devonian periods, about 400 million years ago.

Figure 9.18 Animals like these Mesozoic reptiles were very common in the shallow seas that covered large areas of North America during the Mesozoic Era. Most swimming reptiles became extinct at the end of that era. Their places in the environment were taken by whales, porpoises, and other mammals. Their jaws were not adapted for chewing. Some of them swallowed stones to help grind their food.

THE MESOZOIC ERA

The Mesozoic era, from about 225 million to 65 million years ago [**4 m, 43.5 cm**], is the middle time of abundant life on Earth. Reptiles ruled the land; the era is often called "the age of reptiles." However, slow changes were happening that led to a new major form of vertebrate life, the mammals. Birds also appeared and took successfully to the air, where before only insects and a few ill-adapted reptiles could go.

Reptiles. In the Mesozoic era, the reptiles completely dominated the land. Some even went back to the sea, the watery home of their remote ancestors. Their feet changed to paddle-shaped fins. Their bodies became streamlined; some of them became what we would describe as sea serpents. Some grew to 15 meters in length. They learned to take care of their young while in the water (Figure 9.18). Today we can still see how

6. A lobe fin has bones and muscles extending out into the fin; a ray fin lacks this bone-muscle arrangement. The lobe fin is well suited for use on land as a primitive appendage for locomotion.
7. Amphibians must go back to the water to reproduce and generally must maintain a moist skin. A toad is an amphibian; the "horned toad" of the desert is really a reptile.
8. Reptiles. Their on-land breeding and their shelled eggs allowed a much wider colonization of land by vertebrates.

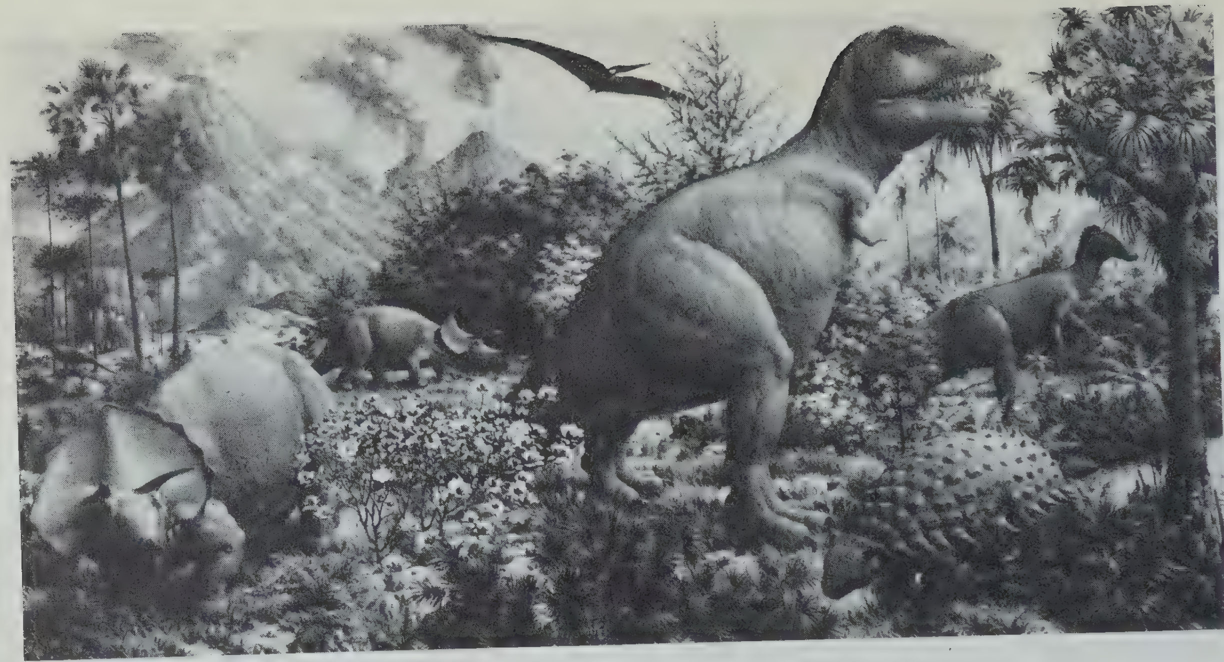


Figure 9.19 Over 70 million years ago, in late Cretaceous time, dinosaurs like these walked the plains of the western United States. The largest meat eater known, *Tyrannosaurus*, stood about 6 meters high. Flowering plants, which first appeared in Mesozoic time, are also shown. (Compare them with the nonflowering plants shown in Figure 9.15.) Since these reptiles were cold-blooded, they could not have withstood our modern western winters in Wyoming or Montana. The climate must have changed.

marine reptiles are tied to the land. Remember the amphibians going back to the water to lay their eggs? Well, the modern sea turtle, a reptile, will come thousands of kilometers through the sea to a beach near its birthplace just to lay its eggs on land.

On land the reptiles had very little competition from other groups of animals. Some became the largest land animals of all times—the **dinosaurs**. Not all the dinosaurs were huge; some were no bigger than dogs. Some were meat eaters and others plant eaters. The meat eaters often walked on two legs instead of four (Figure 9.19). This enabled them to see farther, run quickly, and use their front feet for grasping food. Some of the plant eaters weighed well over 25 tons and often lived near rivers and lakes so the water would help support their weight. If reptiles were warm-blooded, as we are, they might not have been able to grow so large. Warm-blooded animals need more food to support the high rate of chemical activity in their bodies. If you have a pet cat (a mammal), you must feed it every day, but a pet snake (a reptile) may be fed only once a week or so.

Mammals. The main difference between mammals and reptiles is in their method of reproduction. Mammals, with rare exceptions, develop the young inside the body, and after the young are born, they are fed with the mother's milk. Mam- (1) mals are usually covered with hair, which helps insulate them

(1) There are two rare mammals, the spiny anteater and duck-billed platypus of Australia, that lay eggs. [These mammals belong to the subclass Prototheria (early animals), order Monotremata (one opening).] This reptilian trait (egg-laying) was not believed by scientists when it was first reported. It is hard to believe now. When the eggs hatch, the young lick milk from their mother's fur.

against heat and cold. Like birds, they are warm-blooded—that is, they maintain a body temperature nearly the same no matter what the surrounding temperature. This enables them to live in colder climates than the reptiles normally can. Unfortunately, none of these characteristics show up in fossil skeletons. Other changes must be looked for to tell reptile skeletons from those of the earliest mammals.

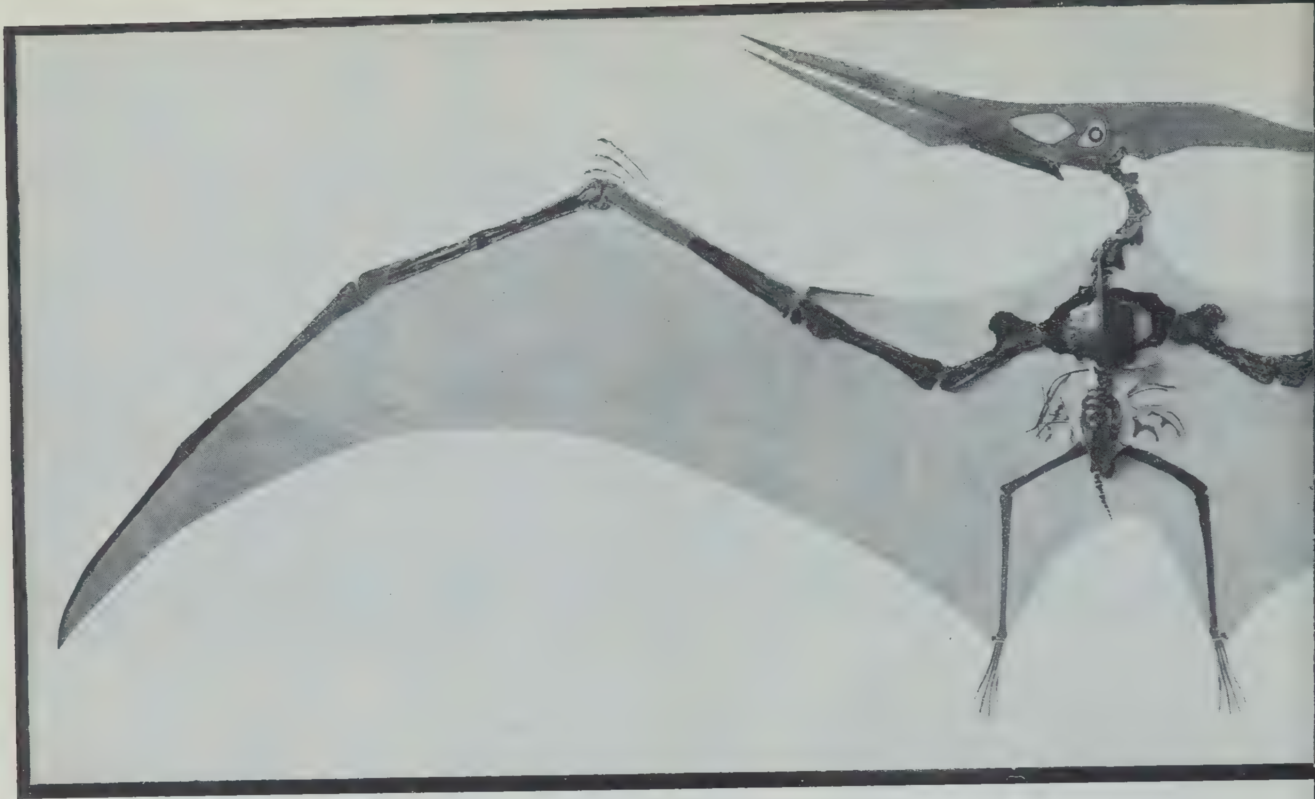
Reptiles usually have teeth that are all alike, differing only in size. An alligator is a good example. Mammals have different kinds of teeth in the jaw—in our own case, biting teeth in front and grinding ones in back. While reptiles usually grab food with their teeth and swallow it whole (go to the zoo during the time when snakes are being fed), mammals bite and chew their food, the most civilized ones with their mouths closed. This allows them a more varied diet. Other skeletal differences also appear in the fossil record. The reptile's jaw and ear bones are not the same as those of mammals.

The oldest fossil skeletons that appear to be of mammals come from sedimentary rocks of late Triassic time, over 200 million years ago [**4 m, 30 cm**]. These early mammals are very reptilelike; there is little doubt that during the constant change, mammals developed from reptiles. These early mammals were small and unimportant and would remain so for many tens of millions of years. Their day was yet to come!

Birds. A few reptiles developed wide membranes between their front feet and rear limbs. These "wings" apparently enabled them to take off and, when there was enough wind, to glide about in search of food. Being cold-blooded, they probably could not generate enough power to flap their wings to stay in flight. Some had wingspans of over seven meters! (See Figure 9.20). In Jurassic time [**4 m, 35 cm**], birds developed from similar reptiles. The earliest bird skeletons are so like reptile skeletons that if impressions of the feathers had not been preserved, scientists would not have known they were birds at all (Figure 9.21). The earliest birds even had teeth, as reptiles have, so the saying "scarce as hen's teeth" is true only for moderns hens. Birds also show their link to reptiles by laying eggs. By the end of Mesozoic time, the flying reptiles could not compete with the birds and became extinct. **(2)**

(2) Geographic isolation, somewhat like that graphically illustrated in Figure 9.5, can lead to some interesting life styles. New Zealand, for example, has been surrounded by ocean so long that no early mammals reached there. Until man came a few hundred years ago, the bat was the only mammal. Many of the ecological niches usually filled by mammals were filled by flightless birds. One of these, the moa, apparently was killed off by man. Some of the moas were 240-360 cm (8-12 ft) high, so perhaps they filled an ecological niche similar to that of our deer.

Flowering plants. In the latter part of the Mesozoic [**4 m, 36 cm**], a change occurred that is almost as important to us as the changes that led to mammals. Flowering plants



appeared. Over 90 percent of living plant types are classed as (1) flowering plants. Flowering plants provide us with nearly all our food. (For example, wheat, rice, and potato are all flowering plants.) Without their development over 100 million years ago, we might never have happened. By the end of the Mesozoic, these plants were the major type on the land.

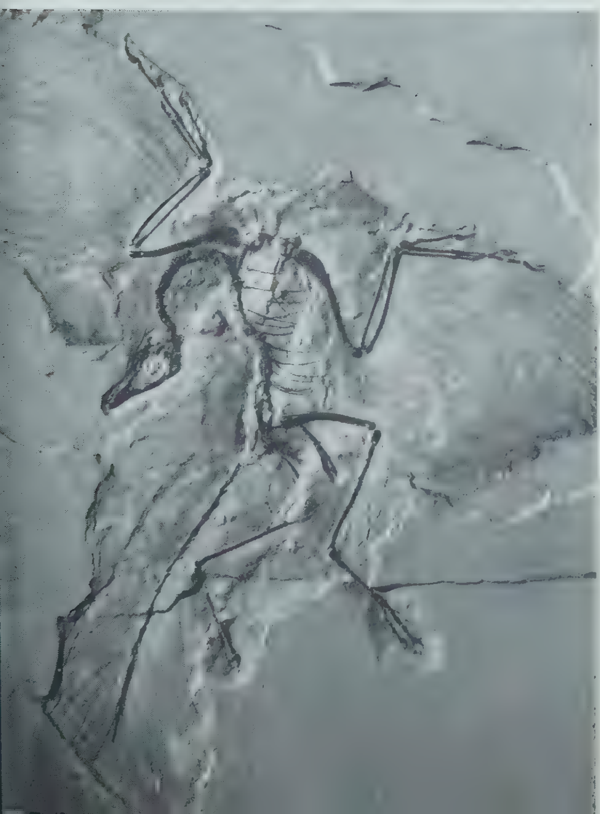
(1) This somewhat ignored milestone in history has had a dramatic influence on terrestrial life. Without flowering plants, the basis of the land food chain, animal life would exist in forms drastically different than those known today. Some of the 7,500 kinds of grasses, as well as the seeds of herbs, shrubs, and trees, played a fundamental part in the development of birds, insects, and mammals. The earliest civilizations were founded on the domestication of flowering plants or of animals that ate flowering plants.

The end of the Mesozoic. Toward the end of the Mesozoic, changes on Earth became quite dramatic. The geosyncline in the western part of North America, which had been filling with sediments since Precambrian time, began major upward movements; the Rocky Mountains were being born. The growth took many millions of years, with periods of relative stillness, and others of more rapid movement and volcanism. Of course, as soon as the mountains rose, rain began to tear them down. It is hard to look at the huge peaks of the Rockies and imagine that they will be gone some day. But they will be.

The continental seas began their final withdrawals in the Mesozoic. More of the land emerged. With the seas now mostly back in their deep basins, the land began to take the shape

Figure 9.20 Nearly 100 million years ago this reptile was flying over what is now Kansas. When it died its skeleton was preserved in the chalky muds on the bottom of a shallow sea. Its "wings" were skin stretched between its front and rear limbs and it had no feathers. A mounted specimen of one of the largest living birds, the condor, is beside it.

Figure 9.21 The fossil skeleton of the earliest known bird, about 150 million years old, is shown at left below. The impression left by the feathers can be clearly seen. In the reconstruction below, you can also see the claws along the front of the wings and the teeth. Without the feather impression as a clue, scientists probably would have called this a reptile. Fossils of birds are very rare.



"Bad news. I hear we're on the endangered species list."

we know today. America and most of the world was never again extensively covered by the continental seas. Of course, it has only been less than 100 million years since the seas were widespread over the United States, and we now realize that's not so much time. The seas may be back.

The end of Mesozoic time [**4 m, 43.5 cm**] is most easily determined by fossils. For reasons we do not understand, many formerly successful animals became extinct. Extinctions occurred in the oceans and on land. The great swimming reptiles, many types of clams, and many other sea animals did not survive the end of Mesozoic time. On land, the dinosaurs, both large and small, became extinct. Why? Many theories have been put forth, but science still waits, and may always wait, for a theory that most scientists will accept. If you try, maybe you can think of some reasons.

Did disease or competition from the newly developed mammals kill the last dinosaurs? Did the flowering plants take over from the plants dinosaurs normally ate, so that the dinosaurs starved? Why did animals of both land and sea become extinct? Perhaps the climate of the world changed. As the seas retreated, maybe the land climates changed too rapidly for dinosaurs to change with them. Also, shallow water environments that had been widespread in the continental seas of the Cretaceous period now existed. only along the coasts of the continents as the seas withdrew. This must have increased competition for food among the sea creatures as they became more concentrated—many did not survive.

CHECK YOUR FACTS

1. What kind of animals dominated the land in the early Mesozoic era?

2. What was the largest land animal of all time?

3. How do birds resemble reptiles?

4. What are some differences between mammals and reptiles?

5. When did flowering plants develop?

6. What were some major events at the end of the Mesozoic era?

(1) (1) **ANSWERS** / Check Your Facts

1. Reptiles.
2. A plant-eating dinosaur.
3. Their bone structures are similar and they lay shelled eggs.
4. Mammals normally do not lay eggs; they suckle their young, they have hair or fur, and they are warm-blooded; their teeth are normally of more than one shape and their skulls and other bone features are different.
5. Late in the Mesozoic era, probably late in the Jurassic period.
6. The Rockies began major uplift and much more of North America rose above sea level. The shallow seas withdrew and many organisms became extinct, most notably the dinosaurs and other large reptiles. Because all this occurred over a period of many millions of years, it was not a catastrophic event.

THE CENOZOIC ERA

From 65 million years ago at the end of the Mesozoic to the present, the continents have stood fairly high. Generally, the mammals have dominated the land and the Cenozoic can be called "the age of mammals." In the sea, the bony fish reached the level of dominance they still have. Of the nonbony fish, only the skates, rays, and the aggressive meat-eating sharks have survived. Sharks have been with us nearly unchanged since Devonian time, almost 400 million years ago! During the Cenozoic some sharks were so large their jaws could open almost two meters.

(2) (2) Sharks do not have the buoyant swim bladder common to the bony fish. They cannot rest nearly motionless and must either swim during their entire lives, or sink.

Many types of mammals developed during the Cenozoic. Some, such as whales, returned to live in the sea. (Remember how some reptiles did the same thing?) Others, such as dogs and cats, became meat eaters. Many more mammals became plant eaters, such as horses, cows, and elephants. Some mammals eat both meat and plants; the best known of these is man.

As the mammals spread through nearly all the environments of the world, their ancestors, the once world-dominant reptiles, could not compete very well. Only the snakes, turtles, lizards, and crocodile types have survived. The mammals, small to begin with, took over the Cenozoic land very rapidly.

Four changes seem to have been occurring to most mammals since their early beginnings: (1) They kept getting larger (see Figure 9.22). The first horses, camels, and elephants, for example, were about as big as dogs. One result of this size increase is the blue whale, the largest animal that ever lived. Over 30 meters long, the adult may weigh over 150

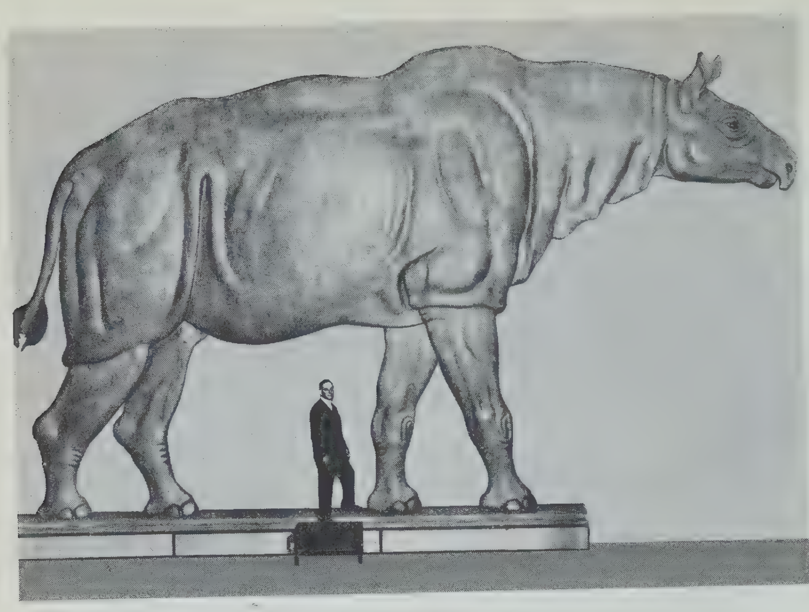


Figure 9.22 After the dinosaurs became extinct about 65 million years ago, mammals became the main land animals. Some grew very large. The photograph shows a reconstruction of a hornless rhinoceros that stood about 5 meters high and lived about 25 million years ago.

tons. (Only a few are still living; most of them have been killed by man.) (2) Their teeth became specialized according to their eating habits. (3) Their feet became better adapted to their environments. On some, toes developed into hoofs, and legs got longer to allow greater speed; others took advantage of changes in the front feet that enabled them to grasp and hold food. (4) Their brains became bigger in relation to their body weight. This was the most important change! The reptiles had, and still have, small brains for their size. Their brains are limited to controlling their senses, such as smell and hunger. The brain sizes of most of the mammals increased during the Cenozoic, and the part of the brain used for memory increased most of all. If you want to test a reptile's brain against a mammal's, try to train a snake or small alligator to come when you call, to beg for food, or to jump through a hoop. On the other hand, most dogs, cats, pigs, and many other mammals—including baby brothers and sisters—can easily learn to do these things. It's no wonder, with such a brain, that mammals rule the Earth.

Primates. Man, along with apes, monkeys, and some other animals, is classified into a group of the mammals called **primates**. Primates have several characteristics that set them apart from other animals. Two of the most important of these characteristics are the placement of their eyes and the shape of their paws (or hands). The eyes are placed in the front of the head, which makes depth perception possible. And with fingers on one side of the hand and the thumb opposite, pri-

mates can grasp things. Our hand has allowed us, man, to advance from the use of stone tools to the ability to put together a spacecraft or a watch.

Parts of small primate skeletons have been found in sedimentary rocks over 60 million years old [**4 m, 44 cm**]. As the early primate mammals developed, several main types came into being. The apes and monkeys began to appear about 35 million years ago [**4 m, 46.5 cm**]. The monkeys developed in two regions; South American monkeys can use their tails almost like a fifth paw, and the monkeys of the rest of the world have tails that are not so useful. The apes are easily seen to be different from monkeys: They have no tail. Their brain is larger than that of monkeys, and they lead a more social life. Their faces can be very expressive and some, chimpanzees, are said to make over 30 sounds in communication.

In late Cenozoic time, a change in climate caused many forests to be replaced by grasslands. Though most primates stayed with the retreating forests (where they originally arose), one type of primate was changing and adapting to life on the ground. His hind limbs lengthened and his feet flattened, making it easier to stand and search the horizon for food and enemies. The ability to stand and to move rapidly on his hind feet freed his front limbs for uses other than moving through the trees. Already developed for grasping, the front hands could be used more and more to pick berries and nuts or grab small animals and insects. These primates began to differ more and more from the apes.

The first manlike animals are known from rare fossils found in rocks over 10 million years old [**4 m, 49 cm**]. The story of the changes and developments of these animals is very poorly known. If you remember how rare fossil preservation of vertebrate land animals is, you can easily understand the problem. Although our feet, our hands, and our posture are all different from those of other primates, it is in our skull that we are most different. Our rows of teeth are circular curves, while those of apes are more U-shaped and have enlarged canine teeth for piercing (Figure 9.23). Also, man now lacks the bony ridge above the eyes found in the ape skull, and man's face has flattened.

It has only been within the last 2 million years that the changes in earlier primates resulted in what we would call "man." The earliest men had brains that were only slightly larger than that of a modern ape. In modern man, the brain is three times as large as that of an ape. This brain has allowed us to develop a behavior that is so different from that of

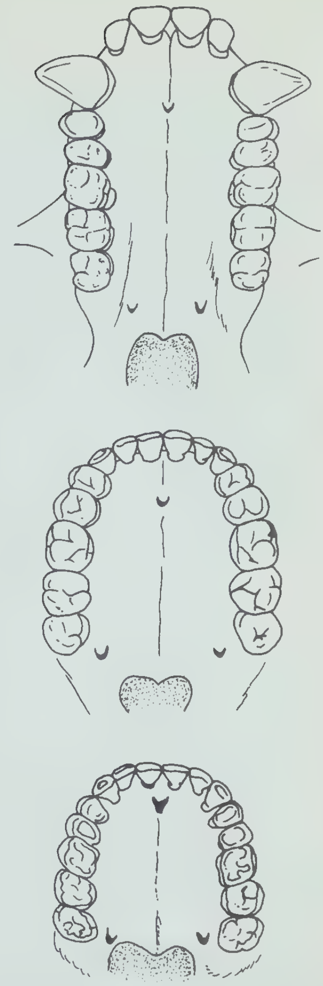


Figure 9.23 One of the most commonly preserved parts of primate fossils is the jaw. This is lucky, because the teeth and their shape are important for distinguishing ape jaws from human jaws. At the top is a drawing of the upper jaw of a gorilla, with its typical sharp biting teeth and the squarish, U-shaped tooth pattern. In the center is a drawing of the upper jaw of a type of man that lived as early as 2 million years ago. This and the drawing of a modern man's jaw below show the absence of pointed "canine" teeth and the more circular overall tooth pattern.

any other primate that any skeletal differences appear small and insignificant in comparison. Reasoning, laughing, and talking separate us from all other creatures much more than our bones and teeth do. The last part of the Cenozoic is "the age of man." On the time tape, draw a line across the tape 4 meters 50 centimeters from the beginning. This is the final line and to the right is the future.

As you read this chapter, you have seen that nothing on Earth remains the same forever. If we see continents, mountains, plants, and animals only in terms of our own short lives, they seem constant and unchanging. But now you should be able to look at them in terms of geologic time. Rain and rivers change the land, new mountains will rise and ones now high will wear away. Man is carried along in the process of change as time goes on into the future. But man is fantastically different from anything that ever lived before. He not only changes, but he has the power to change Earth. Once man lived so close to nature that he was just a small part of the living world. Now he often pays no attention to nature. In the effort to make our world an easier place in which to live, we sometimes forget that it's more important to keep it a nice place in which to live. The future for man, if he uses his huge brain, is just beginning. Look at your time tape: 4.5 meters long, and the time of man is only the thickness of a pencil lead.

CHECK YOUR FACTS (1)

1. What animals dominated the land in the Cenozoic era?

2. What are some important ways in which mammals changed?

3. What is the distinguishing characteristic of primates?

4. How does man differ from other primates?

APPLYING WHAT YOU HAVE LEARNED (2)

1. What is the source of most of Earth's internal heat?

2. If you look inside the mouth of a cat or dog, how can you tell the animal is a mammal and not a reptile just by the shapes of the teeth?

3. You have learned that mammals developed on land, but a few have returned to the sea to live. Yet they have not changed back to breathing through gills or laying eggs. (The whale, for

(1) ANSWERS / Check Your Facts

1. Mammals.
2. Their brain size increased, they got larger, their teeth became more specialized according to their diet, and their feet became more specialized according to their life style.
3. Primarily, the placement of their eyes, which permitted depth perception, and the development of an opposable thumb, which permitted more efficient grasping. These ancient factors, built into the biological nature of people, makes some very complex actions relatively easy. For example, driving a car, with all the complex variables of avoiding another car in motion on a convergent angle, is a relatively easy thing to teach a fourteen-year-old human, but a computer would have to be very sophisticated to substitute for a human driver.
4. Man has a much larger brain. The other (structural) differences are not so important. Man has a more circular tooth pattern, a hand capable of more delicate feats than those of other primates, and a different hip structure, which permits an upright posture.

(2) ANSWERS / Applying What You Have Learned

1. Radioactive decay, mostly of isotopes of uranium, thorium, and potassium.
2. Mammals have teeth of more variable shapes.
3. Penguins. They spend much of their lives in the water where they feed. They nest and rear their young on land.
4. Dinosaurs were extinct tens of millions of years before man was on Earth.
5. Either a nearly horizontal thrust fault moved Paleozoic rocks over Cretaceous ones, or a large fold developed that lay on its side and was then partly eroded. Some of the larger faults of this type moved rocks tens of kilometers horizontally.

example, breathes through lungs and gives birth to its young alive.) Can you think of a bird that has partly returned to the sea? (It spends much of its time in the water.) Can it lay its eggs in the ocean?

4. You may have seen movies in which dinosaurs chased "cave men." Why was this impossible?

5. If you were looking at sedimentary rocks in the mountains and found Cretaceous clams and then found a trilobite fossil in nearby horizontal rocks above the Cretaceous one, what might have happened?

KEY WORDS

principle of superposition (p. 172)
correlation (p. 172)
isotope (p. 181)
radioactive (p. 181)
half-life (p. 181)
geologic time scale (p. 183)
shield (p. 186)
trilobite (p. 188)
continental sea (p. 189)
invertebrate (p. 191)
vertebrate (p. 191)
ray fin (p. 194)
lobe fin (p. 194)
amphibian (p. 195)
reptile (p. 196)
dinosaur (p. 198)
primate (p. 204)

unit three

Land, Air, and Sea

Because we spend most of our time on the land, we tend to forget that the oceans and the atmosphere are as important to us as the surface on which we live. The oceans, covering over 70 percent of the surface area of Earth, influence the weather and climate of continental areas; they provide much of the oxygen that we breathe; and they provide a vast amount of food. The atmosphere is also terribly important to us. The oxygen and other gases it contains are essential to life, and the way it transmits solar energy keeps Earth warm and livable. But the surface on which we live is obviously important too, and its great variety of landscape makes it interesting to live on.

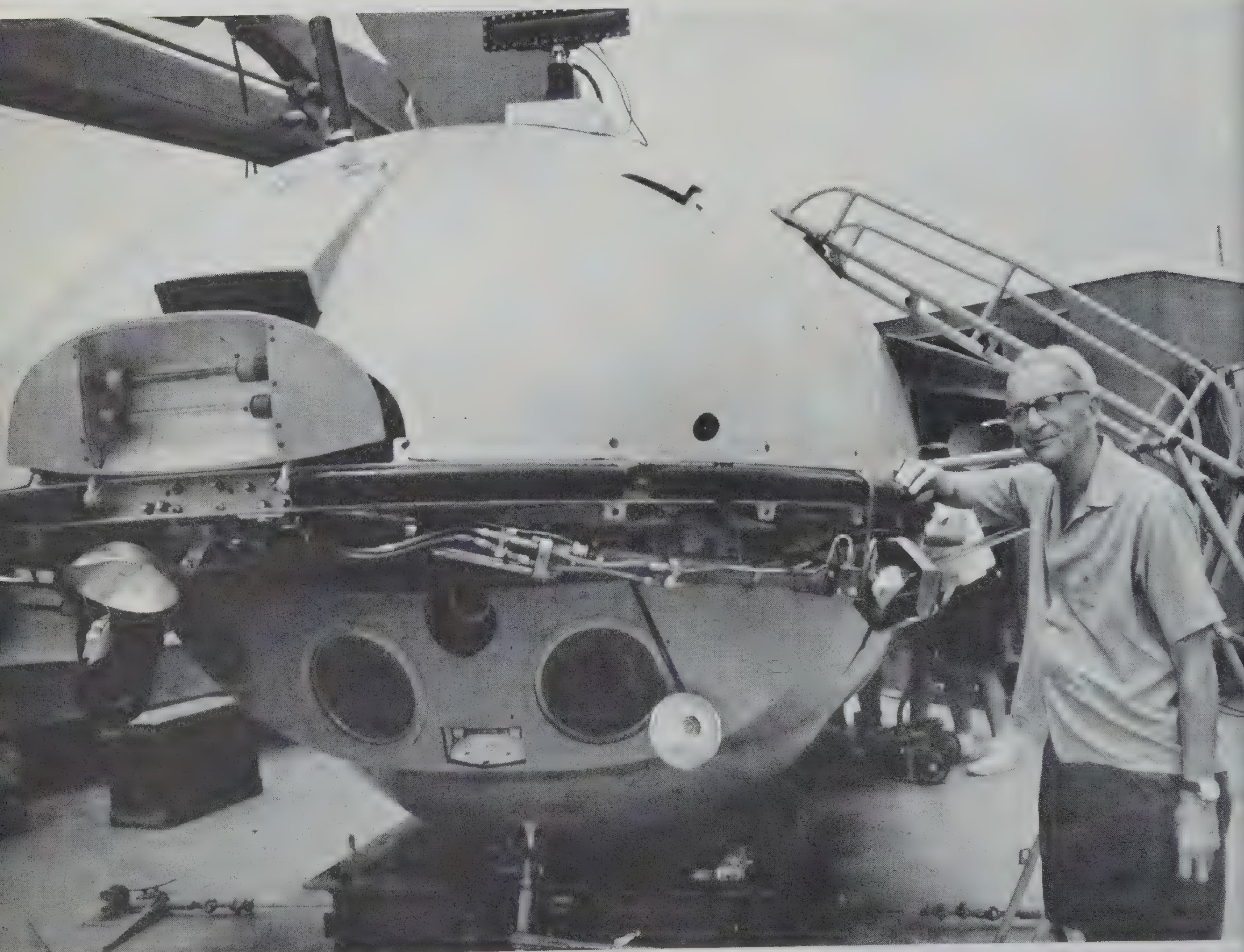


Figure 10.1 The American oceanographer Francis Shepard stands next to a submersible craft used for ocean research.

Introductory Demonstration

Show the color film "Deep Frontier" (M-H).

chapter 10

The Ocean Basins

Earth science is all wet. Well, at least 71 percent of it is. Because that's the amount of Earth's surface that is covered by the oceans. A look at a world map or a globe quickly shows you how much ocean there is. Even in the Northern Hemisphere, where most of the land is, there is still more ocean than there is land. The globe also shows you that all the oceans are interconnected.

To simplify matters, oceanographers (scientists who study the oceans) recognize only three major oceans—the Atlantic Ocean, the Pacific Ocean, and the Indian Ocean. Oceanographers realize, of course, that these oceans are connected. Smaller seas, like the Mediterranean Sea and the Caribbean Sea, are considered parts of the larger oceans to which they are connected. The Arctic Ocean is considered part of the Atlantic rather than the Pacific. Why do you suppose this is so? **(1)** (For the answer, look at a globe rather than a map—preferably a globe that shows ocean currents.)

(1) The Arctic Ocean is considered part of the Atlantic Ocean because it is in open circulation with it. Water entering the Arctic along the coast of Norway circulates through the Arctic Basin and reenters the main portion of the Atlantic between Iceland and Greenland. Circulation between the waters of the Arctic and Pacific oceans is extremely limited. The amount of water moving through the Bering Straits from the Arctic to the Pacific or vice versa is very small.

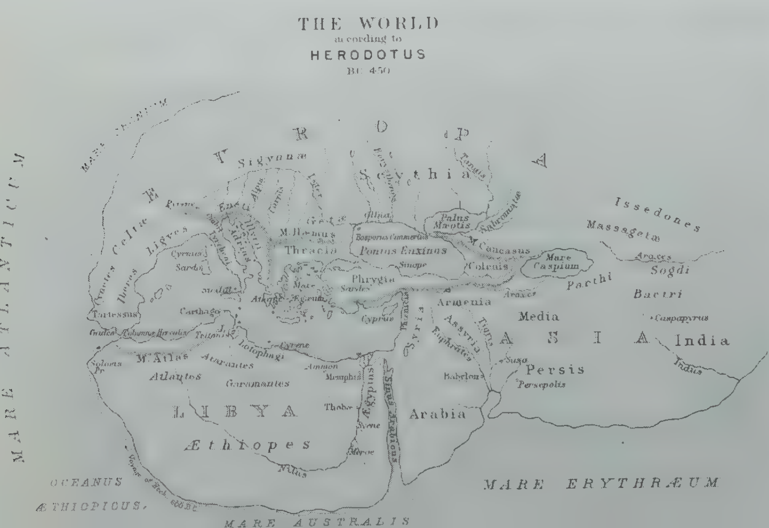
OCEAN MAPS

The seas must have fascinated man from his earliest days. Figure 10.2 shows a map of the world made by the ancient Greeks. As you can see, the Greeks knew the Mediterranean Sea pretty well, but their knowledge of more distant areas was not very accurate, to say the least. Eventually, however, knowledge of the oceans beyond the Mediterranean developed. In the early days, such knowledge was considered to be of military value. Maps were top secret documents. When there was a danger of capture by the enemy, every effort was made to destroy the maps so they would not fall into the enemy's hands. Most maps were destroyed at one time or another, so our knowledge of what the ancients knew about the oceans is fairly vague. We do know, however, that before the birth of Christ the ancient peoples of the Mediterranean had sailed completely around the coast of Africa, and they had sailed as far north as the Arctic Ocean.

By the time Columbus made his trip, much of the secrecy about maps had disappeared and the geography of Europe and Asia was fairly well known. Earth was believed to be round, and there seemed little doubt that with enough supplies and good humor, men could sail from Europe to Asia by traveling from east to west, rather than from west to east. There were, of course, doubters who claimed that Columbus would fall off the edge, or would be eaten up by some deep-sea monster. (As it turned out, of course, Columbus didn't end up in Asia at all.) Since Columbus's time, maps have improved

(1) There are, of course, a number of reasons why people have had a very practical interest in the depth of the ocean. They were concerned with water depth wherever they took ships into shallow water, attempted to anchor vessels in protected areas, or sought to recover objects from the bottom of the ocean. As capability for catching fish developed, it became important to know water depth, particularly when fishing for bottom (demersal) fish. With the advent of electricity and the development of the telegraph during the mid-nineteenth century, attempts were made to lay cables across the ocean bottom. The first detailed measurements of water depths were made in the open ocean in order to facilitate the laying of these cables. Construction of man-made features such as jetties, pipelines, and offshore drilling rigs require a knowledge of the water depth.

Figure 10.2 All of Africa is represented by the land between the Mediterranean and "Mare Australis," or the "southern sea."



a great deal. The development of navigational instruments, and today the use of satellites for making maps, have provided us with fairly precise maps of the oceans.

Measuring depth. Most ocean maps today give some (1) indication of the water depth, either by color (usually by different shades of blue), or by means of contour lines or by numbers showing the depths at various points. An early method for measuring water depth was to lower a weight at the end of a line. There is a story that Columbus tried to measure the ocean's depth by tying together all the rope he had available. He actually managed to put together 350 meters of line, which was lowered into the water. Unfortunately, he was over a depth of 4300 meters at the time!

(2) A fathom is 6 feet (or 1.83 meters). Several centuries ago, when water depth was measured by means of a lead line (or sounding line), fathoms were counted by stretching the line from one hand to the other with the arms fully extended—a distance of approximately 6 feet. Thus, a seaman would count one fathom each time the line was stretched from his left to his right hand. The depth of 2,425 fathoms measured in the South Atlantic was thus approximately 4,400 meters (14,550 feet).

The first successful measurement of depth in the deep sea was made in 1840, from the British ship *Erebus*. The measurement, 2425 fathoms (4435 meters), was made in the central (2) part of the South Atlantic. The depth was measured by using a reel and line similar to what fishermen use. A weight was attached to the end of the line. The line was allowed to run free from the reel, and the bottom was identified when the speed at which the line was coming off the reel suddenly slowed down. (Is this a very accurate way to measure water depth?) (3)

One *fathom* is equal to 6 feet. Although metric units (for example, the meter) are used in most sciences, the fathom, a British unit, is frequently used in oceanography for measuring water depth.

(3) Measurements of water depth made by the use of lead lines were not very accurate. In deep water the weight of the line itself was frequently much more than that of the weight at the end of the line. By watching the rate at which a reel turned as the line was let out, it was sometimes possible to determine when the bottom had been reached by a change in the rate. Often it was necessary to pull the weight off the bottom and make several attempts before there could be a reasonable certainty that the bottom had been reached.

Although this first successful measurement of deep water was made in 1840, it wasn't until the voyage of the British ship *Challenger* (Figure 10.3) in 1872 to 1876 that we began to learn something of the general shape of the ocean basins. The *Challenger* sailed all over the world, taking many sound-

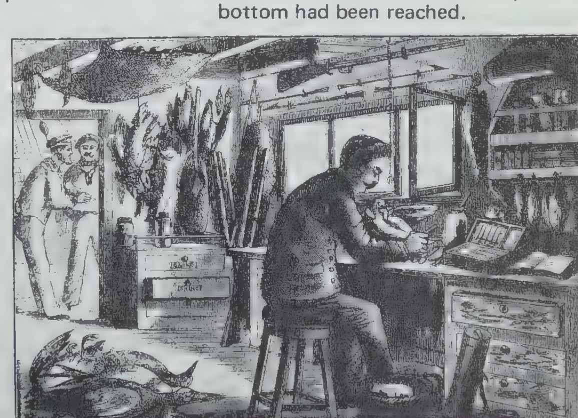


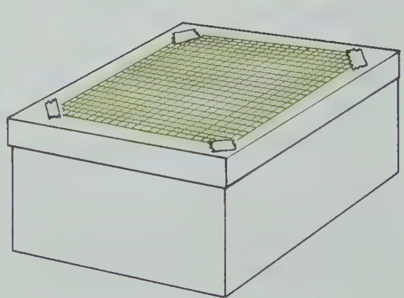
Figure 10.3 The *Challenger* is shown at left passing an iceberg. At right is a drawing of one of the laboratories on the ship.

ings and making other measurements as well. (To take a sounding means to make a measurement of water depth.) This voyage, one of the most successful ocean expeditions of all time, is generally considered to mark the beginning of modern oceanography.

By 1895, there were still fewer than 7000 soundings of water depths of more than 2000 meters. This was an average of about one measurement for every 40,000 square kilometers of ocean. (How many measurements would that be for an area the size of your state? Could you really tell very much about the shape of your state—its ups and downs—from that many measurements?)

(1) **(1)** Obviously, it is virtually impossible to tell much about the shape of anything on the basis of data points approximately 7,200 kilometers (4,000 miles) apart. Nevertheless, our knowledge of the ocean basins toward the end of the nineteenth century was based on a distribution of very few measurements. Many of the measurements were fairly close together, thus leaving vast expanses of sea floor which had not been touched.

activity 10.1 Determining shape by "depth soundings"



For this activity you will need a box with a removable top (such as a shoe box), enough graph paper to cover the top of the box, a ruler, some adhesive tape, and some long, thin rods, such as knitting needles. If knitting needles are not available, pencils or drinking straws will do.

Tape the graph paper to the top of the box. Following the pattern of the graph paper, punch a gridwork of holes through the box top. Your teacher will put an object into the box and replace the top. Now, using your rods or knitting needles to take "soundings" through the box top, figure out what's in the box.

You take a sounding by lowering the rod vertically through a punched hole until it hits bottom. Make a mark on the rod at the level of the box top, draw the rod out, and measure the depth. Remember to write down the location where you take each sounding.

First, take soundings at "widely separated" locations, such as the open circles shown in Figure 10.4. Do these widely separated soundings give you enough information about the shape of the object for you to figure out what the object is?

Now make many more soundings—for example, at every intersection of lines on the graph paper shown in Figure 10.4. You are collecting a lot of data now, so make sure your notes are organized!

Now let's use the data you've collected to figure out the shape of the object hidden in the box. A good way to do this is to make many "profiles" of the object. For example, suppose that the object hidden in the box is a model of a volcano. The

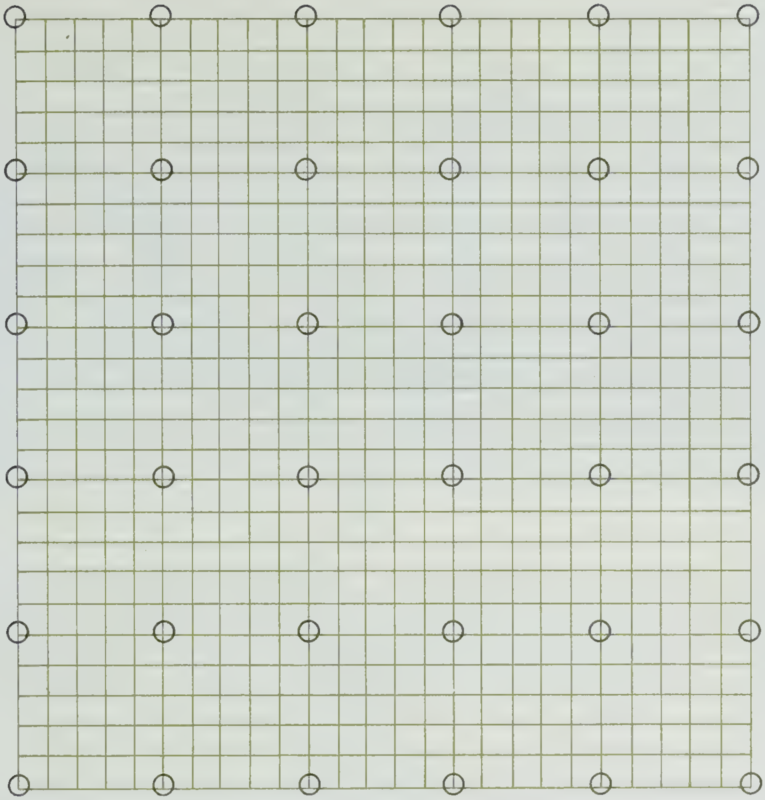


Figure 10.4 Tape a piece of graph paper like this to the box top. Make sure you record the location of each sounding.

(2) It could be a cinder cone or a composite volcano; it is too steep to be a shield volcano.

Figure 10.5 A profile of a volcano might look something like this. What kind of volcano would this be? (2)

profile made along the plane that cuts the volcano in half would look something like Figure 10.5.

Make many profiles and cut them out on cardboard. Copy Figure 10.4 on a piece of graph paper. Glue the bottom edges of the profiles on the graph paper along the lines corresponding to the profiles. (The profiles should stand up vertically from the paper.) Glue down many profiles, and you will get a good idea of the shape of the hidden object.

In the 1930s, oceanographers began to make many profiles of the ocean floor, and from these profiles a detailed picture of the shape of the ocean bottom began to emerge. The oceanographers were able to make many profiles because a very useful instrument, the **echo sounder**, had been invented. An echo sounder sends a sound signal down through (3) the water and receives the echo that bounces back from the bottom. Since the speed of sound in water is known, the distance to the bottom can be figured out from the length of time

(3) The use of sound to measure water depth was developed during the 1920s and 1930s. The method is based on the assumption that the velocity of sound in sea water is relatively constant. This is a reasonable, but not completely accurate, assumption. The velocity is affected by the temperature, salinity, and pressure. For most practical, everyday purposes, a velocity of approximately 1,500 meters per second (4,800 feet per second) is used. The echo sounder consists of a recorder, an amplifier, and an electrical source. An electrical impulse is converted to sound at the *transducer* on the bottom of the ship. Sound signals radiate out from the bottom of the ship in such a way that a cone of sound 60 degrees wide is directed toward the bottom. As soon as the sound strikes the bottom it is reflected back toward the ship. When the reflected sound reaches the transducer it is converted to electrical energy; then it is amplified and recorded. By measuring the elapsed time between the origin of the sound signal and its return, it is possible to calculate the approximate depth of water, using an assumed velocity for sound in sea water.

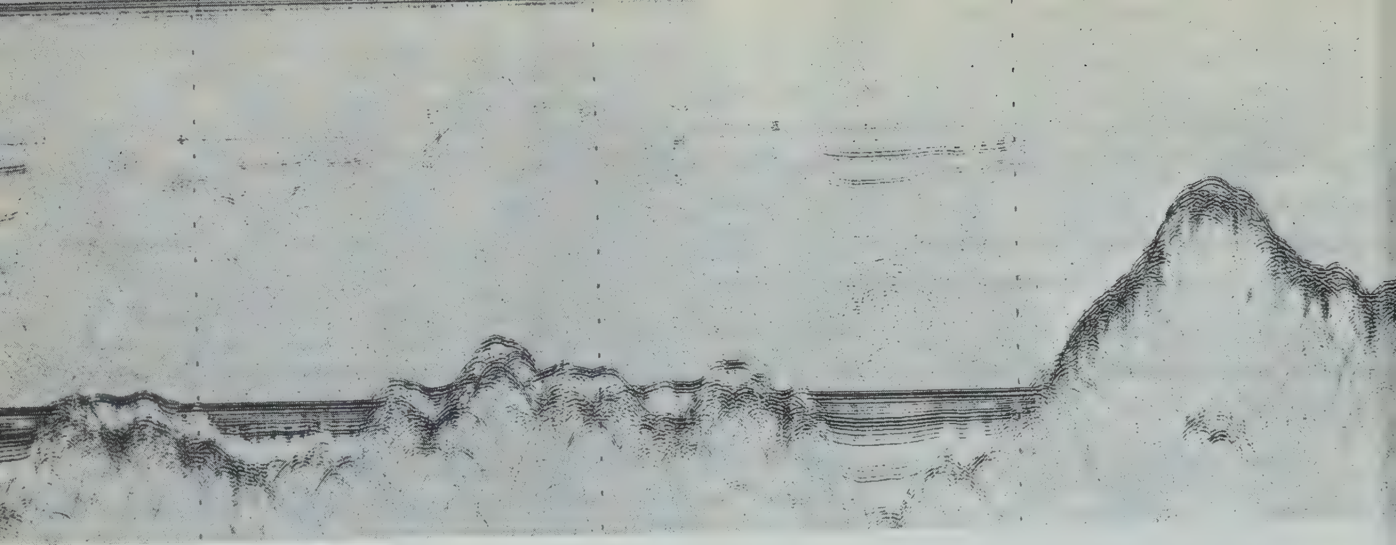


Figure 10.6 This profile of the ocean bottom, covering a distance of about 130 kilometers, was made by an echo sounder that records not just the ocean bottom but also some of the geological features beneath the ocean bottom. The horizontal lines are layers of sediment. The vertical distance is greatly exaggerated.

needed for the sound signal to make the round trip. (This is done automatically in the echo sounder.) By taking many soundings, the echo sounder records a continuous profile of the bottom that the ship is traveling over (Figure 10.6).

CHECK YOUR FACTS (1)

1. About what percentage of Earth's surface is covered by the oceans?

2. What method was used in the first successful measurement of depth in the deep sea?

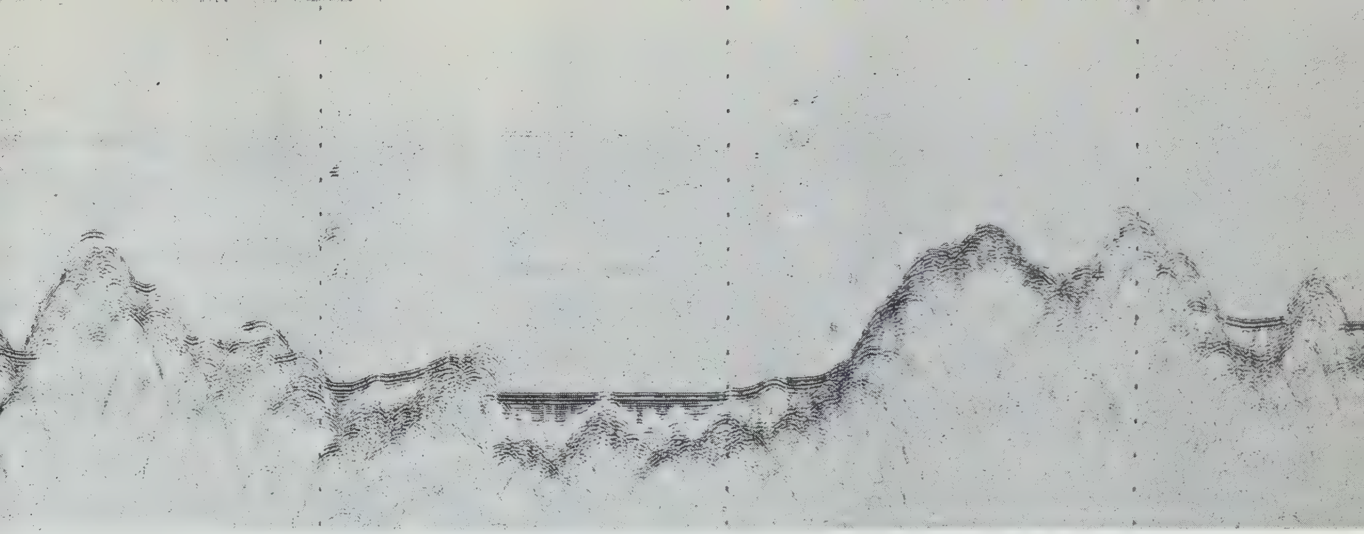
3. How does an echo sounder work?

(1) **ANSWERS** / Check Your Facts

1. About 71% of Earth's surface is covered by the oceans, or to be more precise, 70.8%.
2. The first successful measurement of depth in the deep sea was made by lowering a line with a weight attached. The line was allowed to run free from the reel on which it was spooled. When the speed at which the line came off the reel suddenly slowed down, it was assumed the weight had reached the sea floor.
3. A modern echo sounder sends a pulse of energy (sound) down through the water and receives the echo that bounces back from the bottom. Since the speed of sound in water is known, the distance to the bottom can be calculated from the length of time the signal takes to reach the bottom and return to the ship. The electronic components of the echo sounder convert this information to depth and record it graphically.

THE OCEAN BOTTOM—A MAGNIFICENT LANDSCAPE

As a result of the use of modern depth sounders, we have learned a great deal about the shape of the bottom of the ocean. The map of the Atlantic Ocean in Figure 1.8, for example, was constructed by referring to thousands of profiles of the ocean bottom provided by modern sounders. We now know that the oceans have an average depth of about 4 kilometers. The deepest parts of the oceans are about 11 kilometers deep. The features on the floor of the ocean are much larger than the features on land. In Chapter 6, we compared the height of Mauna Loa, one of the shield volcanoes that make up the island of Hawaii (Figure 6.8), with the height of Mt.



Everest. Do you remember which was higher? You can do the (2) same type of comparison for other features on the floor of the ocean. The deep ocean trenches, for example, are over 10,000 meters deep. How do they compare in depth with the Grand Canyon? Some of the mountain ranges on the floor of the ocean are much larger than the mountain ranges on land. The mid-ocean ridge, for example, extends from Iceland through the entire length of the Atlantic Ocean (the Mid-Atlantic Ridge, labeled MIDA, Figure 1.8), and then on into the Indian Ocean and (another branch) into the Pacific Ocean. How much longer is this ridge than a mountain chain such as the Andes, or the Rockies (Figure 7.14)? (3)

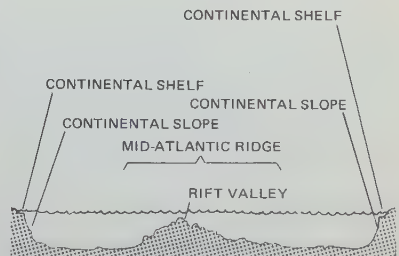
Many of the features that occur on the floor of the ocean are shown in Figure 10.7. Ordinarily oceanographers think of the margin of the continent as being the continental shelf and the continental slope (Figure 6.27). In some places we include the feature called the **continental rise** (the transition zone between the continental slope and the deep sea floor). Where there are no continental rises, deep sea trenches may be found, particularly in the Pacific Ocean. Beyond the continental rise, the deep sea floor may be flat and smooth. In some areas, however, the floor is made up of small hills. In places high peaks rise steeply from the deep sea floor, and near the centers of the oceans are long chains of mountains that make up the mid-ocean ridge. As you learned in Chapter 7, there are many types of mountains. In the ocean, however, almost all of the mountains are volcanic.

The edge of the continents. Let's consider these features of the deep sea floor as we might if we were to take a trip

(2) Mt. Everest has a summit elevation of approximately 8,700 meters. However, the mountain is located in high mountainous country and the base of the mountain is approximately 3,000 meters above sea level. Thus, the relief of Mt. Everest, that is the difference between summit and base elevations, is only about 5,700 meters. It's a fair-sized mountain nevertheless. Have your students determine the size of the Grand Canyon and compute its relief.

(3) Comparisons of sea-floor features with those occurring on land can be made by consulting any good school atlas. The features on the floor of the ocean are generally larger than those on land because first, they are features of the mantle rather than features of the crust, the ocean crust being so thin, and secondly, they are less obscured by details of erosion and deposition.

Figure 10.7 A profile made all the way across the Atlantic would look something like this. South America is on the left, Africa on the right.



from the shoreline out into the deep sea in a submersible like the one shown in Figure 10.1. When you are standing on an ocean beach, you are actually standing on the inner edge of the Continental shelf, which you can think of as the outer edge of the continent, planed off by surf action. The shelf is very flat, almost as flat as a billiard table. It extends from the shoreline on out to a place where the bottom slopes more rapidly in the deeper water. On an average around the world, the continental shelf has a slope of about 2 meters per kilometer. This means that if you walk up a slope the length of a football field (100 yards, forgetting the end zones), you would rise only about 7 inches. Continental shelves vary in width from less than 2 kilometers, off Miami, Florida, to more than 1200 kilometers, off Siberia. The outer or seaward edge of the shelf varies considerably in depth, but around the world has an average depth of about 120 meters. In general, continental shelves are widest and shallowest off coastlines where there are wide, flat, coastal plains, such as the East Coast of the United States. Where the coastline is mountainous, as along the West Coast, the shelf is generally narrow and deep. But everywhere it is pretty flat. How can you explain this flatness? (1)

(1) The flatness of the continental shelf is the result of first, the rise and fall of sea level during the ice ages, and second the abrasive action of the surf zone. As sea level fell and then rose again, the surf zone migrated back and forth, eroding any high areas which existed. Subsequently, lower areas may have been filled in by sediments, thus removing irregularities.

All in all, a submersible trip across the continental shelf would be fairly exciting, but only because it would be a trip in a submersible beneath the ocean surface. Except for fish and other animals, there wouldn't be much to see. The bottom would be smooth except for an occasional rock outcrop. We might see an occasional animal burrow or track on the bottom, but not much else. Things really don't change much as we pass the edge of the shelf and descend into the deeper water over the continental slope. However, in some areas of the world, we might descend into a deep trench and then come up over a ridge before we get to the flat sea floor. Three basic types of continental margins are shown in Figure 10.8.

Geophysicists have developed equipment, similar to that used for measuring water depth, that tells them what the layering of sedimentary rocks is like beneath the surface. On (2) the basis of records from these devices we now know that the rock layers beneath the continental shelf and slope may be flat or they may be folded and faulted. This type of information is very important to oil companies because oil often accumulates in such folded rocks.

(2) Geophysicists use instruments which operate very much like echo sounders. However, instead of using a sound of relatively high frequency they use low-frequency sound which has the ability to penetrate the sediments and rocks beneath the sea floor and which is reflected from discontinuities *beneath* the sea floor. These discontinuities are present as bedding plains, erosional unconformities, and so on. The technique is actually similar to that of the echo sounder, but different types of sound sources are used. One type uses a spark which is generated in the sea water and makes a sound as the spark jumps between electrodes. Another type releases compressed air, giving a noise similar to that obtained by popping a paper bag filled with air. As with the echo sounder, sound is reflected and recorded.

Submarine valleys. A common feature on the outer part of the continental shelf and slope are **submarine valleys**, also called **submarine canyons**. There are many different

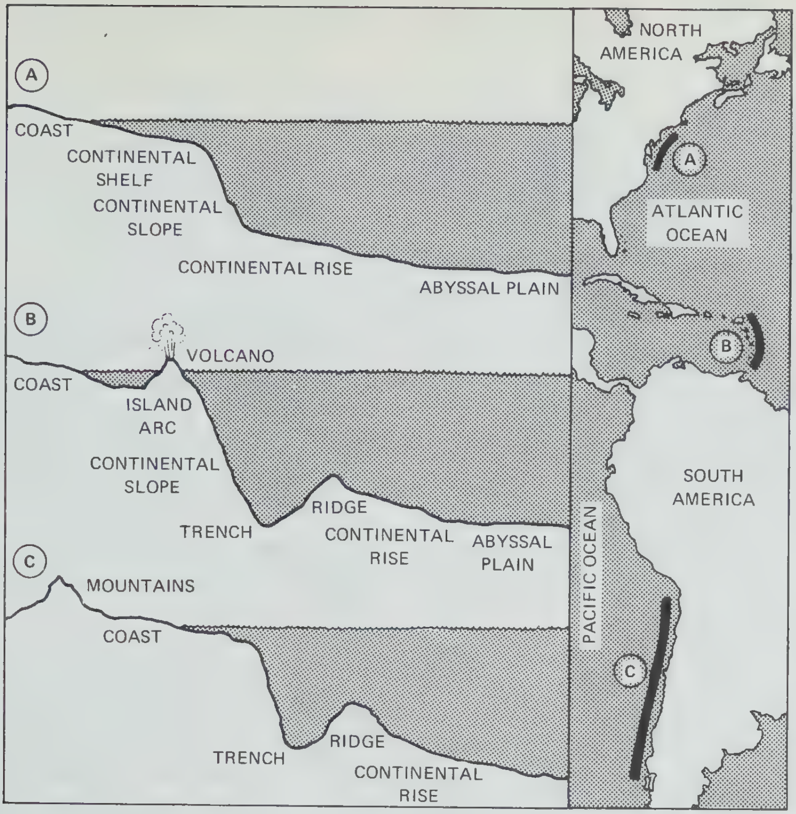


Figure 10.8 These types of continental margins are found not only around the American continents, as shown here, but all over the world. The type shown in B, for example, is found along the western edge of the Pacific.

types of submarine valleys. Some have winding courses, V-shaped profiles, steep walls with many rock outcrops, tributaries, and so on. Some are trough-shaped, have straight-walled valleys, and lack tributaries. There are short gulleys occurring off deltas and the continental slope; and there are long, broad channels that cross the flat, deep-sea floor. In short, there is almost every kind of submarine valley you can imagine.

Many submarine canyons are located off major rivers; many occur where no rivers presently exist. Some have their upper part very close to the shoreline; others occur farther offshore. Those submarine valleys that come in close to shore might have a practical value because they bring deep water close to shore. Some people have considered dumping garbage in them. Do you think this is a good idea?

(3) You get into ecology and the degradation of the environment on this one. You're on your own, and your class may come up with an excellent discussion session here.

The origin of submarine valleys has been one of the most perplexing problems in marine geology and has not been completely solved. In the early days of their exploration, the easiest explanation seemed to be that the valleys were the result of normal river and stream erosion, and that after the erosion, sea level had risen and had submerged the valleys. However, as more and more data became available, it was obvious that

there were certain problems with this explanation. It was found, for example, that many submarine valleys extended into water 3000 meters deep. This would mean that sea level had come up 3000 meters since the canyons were formed. But many canyons were estimated to be only a few thousand years old. Does it seem probable that sea level could rise that rapidly? (1)

Faced with this problem, some geologists came up with another explanation. They thought that the submarine valleys might have been formed through erosion by turbidity currents. (Remember turbidity currents from Chapter 4?) A great many experiments were carried out to determine whether turbidity currents could, in fact, erode hard rock on the floor of the ocean. Not all of these experiments were successful. More recent studies have shown that much of the sediment in submarine valleys is very slowly slipping down the valley, moving much the way a glacier does down a mountain valley. The slow grinding action of the sediments against the walls of the valley does cause erosion. According to one explanation, the upper part of the valley originated by stream erosion when sea level was lower during the Ice Ages. As sand, which (2) was moved in the surf zone, encountered the valley, it dropped into it and acted as an abrasive, like sandpaper. Under the force of gravity the sand moved very slowly down the valley, cutting the valley deeper and deeper down the slope. From time to time, storm waves would churn up the sediments in the valley, which would move very rapidly as turbidity currents. The turbidity currents were more effective in cleaning out the canyons than in actually eroding them.

This explanation uses three mechanisms to explain the origin of valleys—normal river erosion, slow movement or creep of sediments, and turbidity currents. Probably most of the submarine valleys in the world can be explained by using this combination of processes.

Plains and hills. Turbidity currents flow in response to (3) gravity. Because of this they carry sediments to the deeper parts of the ocean. These sediments cover irregularities in the ocean floor and in time, barren flat plains are developed. These **deep-sea plains**, or **abyssal plains**, exist only where turbidity currents can reach the deep ocean floor to deposit sediments. In the Pacific Ocean, deep-sea plains are scarce and of limited size. Can you think of why this may be? Many (4) relatively small deep-sea plains in the Pacific are in the bottoms of the deep-sea trenches. Seaward of the trenches the

(1) Most geologists do not feel that sea level could rise as rapidly as is indicated by this concept. Another objection to lowering sea level by evaporation to this depth is that the salinity in the remaining water would have become so high that very few of the organisms which we know today could have survived. You might have some of your students attempt to calculate what the average salinity of the remaining ocean would be if 10,000 feet of water were removed from an ocean averaging 12,500 feet deep.

(2) Those valleys that come close enough to shore to intercept the zone in which sediment is moving along the coast are usually floored with sand. Sand is common on the inner parts of the continental shelf. Frequently, finer-grained sediments occur on the middle and outer portions of the shelf. Those valleys which have their heads farther offshore thus accumulate the finer-grained sediments rather than the sands which move from the active inshore zone down through the valleys to the deep sea.

(3) At the point where the slope of the sea floor decreases, the velocity of turbidity currents also decreases. Sediment which is carried under high velocities is deposited as the velocity decreases. As this sediment accumulates it begins to form a bulge in the sea floor. The flow of turbidity currents seeks the steeper slope and with time swings from one side of the canyon mouth to the other, thus forming a fan.

(4) Deep-sea plains are scarce and of limited size in the Pacific because of the number of deep-sea trenches surrounding the margin of the Pacific. These trenches act as traps for the turbidity currents which carry sediment away from the continental areas towards the deeper parts of the ocean. The turbidity currents are ponded in the deep-sea trenches and deposit their sediments in those areas, thus creating long, linear, deep-sea plains in the bottoms of the deep-sea trenches.

floor of the ocean is not flat and smooth, but rather consists of many hills.

Most deep-sea hills are only a few kilometers wide and a few hundred meters high. They are the most common feature on the floor of the ocean and occur over wide expanses of the deep sea where turbidity currents have not deposited sediments. It has been estimated that as much as 50 percent of the floor of the Pacific consists of these small hills.

The larger hills and peaks (those that rise more than 1000 meters from the sea floor) are called **seamounts**. There are probably more than 20,000 individual seamounts on the floor of the ocean. Almost all of them are volcanoes. However, some of them do have coral reefs of limestone perched on their summits. In a number of places seamounts occur as long lines of individual volcanoes. Do you know of any islands that are seamounts exposed above the sea's surface? (5)

Most of the seamounts in the ocean have fairly pointed summits, but there are some with flat tops. Some of these have about a kilometer of water above them. Geologists now conclude that at least some of these flat-topped seamounts stood at sea level and were flattened by the surf. Can you think of (6) any evidence that might be used in support of such an explanation? Can you think of any reason why these seamounts are (7) now at great depth?

Mid-ocean ridges. The vast majority of seamounts are part of a long ridge of mountains that extends from the Arctic Ocean down through the Atlantic into the Indian Ocean and around into the Pacific (Figure 10.9). Generally, the crest of this ridge is more than 1800 meters below sea level, but in a few places it reaches above sea level as isolated islands; Easter Island in the Pacific and Iceland and Ascension Island in the Atlantic are part of the mid-ocean ridge. Over much of its length, particularly in the Atlantic, the center of this long ridge is marked by a deep valley that runs along the length of the ridge. Would you expect valleys on land to run parallel to the crest of mountain ranges or at right angles to them? Why? How might you explain the origin of a valley that runs along the crest of a ridge? (8)

In many places the deep valley, called a **rift valley**, is deeper than the base of the mountains beside it. The floor of the valley is flat, covered by sediments in many places, but in others it is rough with volcanic rocks on the bottom. The rift valley is the site of many earthquakes. Although you have already seen that most earthquakes occur around the edge of

(5) The Hawaiian Islands are excellent examples of islands that are seamounts which have extended above the sea surface; they also provide an excellent example of places where seamounts are still forming. That is, the islands are still volcanically active.

(6) Shortly after the flat-topped seamounts were discovered, samples were taken from a number of them in the mid-Pacific. These samples included fossils of shallow-water organisms that had been alive approximately 60 to 70 million years ago. The shallow-water nature of the present-day counterparts of these fossils suggested that they were formed in water only a few meters deep.

(7) Because of the fossil incidence, we may conclude that either the mountains have sunk or sea level has risen some 1,000 to 1,300m during the last 70 million years. From other evidence we believe that sea level has been fairly constant during this period of time. Thus, the sea floor with the seamounts must have subsided during the past 70 million years. Other evidence for the subsidence of the sea floor is found in coral reefs. During his voyage on the Beagle, Charles Darwin noticed that there were a number of different types of coral reefs and reasoned that all these types might be related in their development. He reasoned that the different types of reefs could be explained as resulting from the sinking of a volcanic seamount on which coral originally began to grow near the shoreline. As the seamount continued to sink, the coral grew upward to the surface of the water as fast as the seamount sank. This resulted in a separation of the coral reef from the island and finally in the forming of a ring of coral after the volcanic peak had sunk below the sea surface. This general theory of subsidence has been tested by drilling through coral on islands to determine the nature of the foundation beneath the coral. These tests have shown that Darwin was right, and that these large seamounts have actually sunk below the surface.

(8) Valleys on land are, for the most part, due to erosion. This erosion is caused by running water which moves down slope; thus the water runs at right angles to the crest of the mountain ranges and thereby produces valleys which are normal to the crest. Obviously, valleys which run parallel to the crest or at the crest are then due to other types of geologic processes. Most such valleys are the result of tectonic activity, that is, the fracturing and pulling apart of Earth's crust. A valley which runs along the crest of the mid-ocean ridges is this type of valley, termed a rift valley. It results from a pulling apart of Earth's crust.

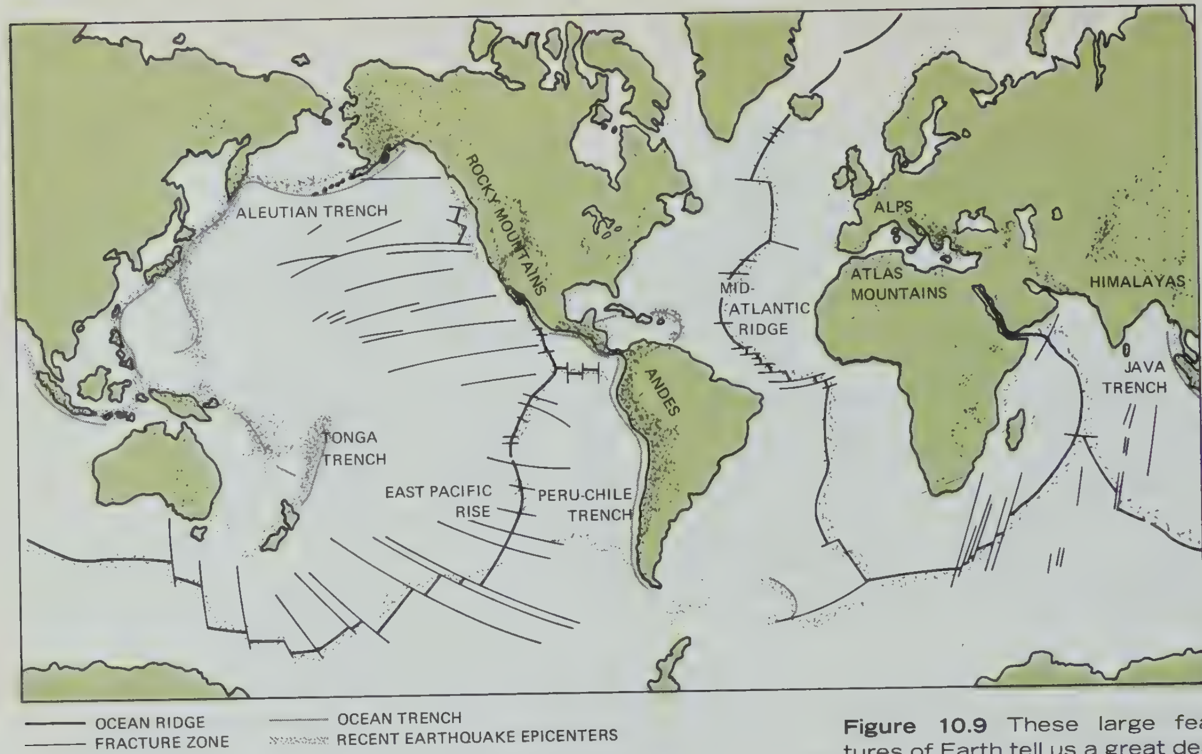


Figure 10.9 These large features of Earth tell us a great deal about Earth's history—and its future.

the Pacific Ocean, in the Atlantic most earthquakes occur in the rift valley in the center of the ocean. Geophysicists have also been able to determine that the flow of heat from the floor of the ocean is higher in the rift valley than it is anywhere else in the ocean. In many places it is five or six times as high. The higher heat flow and the earthquake activity suggest that the mid-ocean ridge is active geologically.

In many places the mid-ocean ridge and the ocean floor to either side appear to be broken by large cracks (Figure 10.9). The crest of the ridge may be offset (displaced sideways) on either side of the cracks. These cracks, or **fracture zones**, appear to be places where Earth's surface has broken into large blocks. The earthquakes associated with the mid-ocean ridges appear to be located along the portions of the fracture zones that separate the rift valley. Later in this chapter we'll see how earth scientists explain the origin of some of these features.

Deep-sea trenches. Probably the only features on the floor of the ocean that rival the mid-ocean ridge in size and complexity are the **deep-sea trenches**. What do you notice about the distribution of the trenches in Figure 10.9? Where are most of them located? These trenches, which are many hundreds of kilometers long but only tens of kilometers wide,

are of the order of 6000 to 11,000 meters deep. A great many of them have flat floors covered by relatively coarse sediment. Could you explain why this might be? (1)

Like the mid-ocean ridges, the trenches are very active areas geologically. Most of them are close to active volcanoes. Also, most of the world's earthquakes are associated with these areas. It has been estimated that almost 80 percent of all of the shallow earthquakes of any size occur in the vicinity of the trenches; almost 90 percent of the intermediate depth earthquakes and almost all of the deep earthquakes take place adjacent to the areas of the trenches. If you have plotted these on a cross section of one of the trenches you will see that the earthquakes take place along a zone dipping about 45° in most places toward the continents (Figure 10.10). How might you explain this? (2)

(1) The accumulation of coarse sediment on the floor of the trenches is due to the action of turbidity currents which carry this sediment from shallow water to the deep sea floor. After reaching these deep depressions the turbidity currents are ponded, lose their velocity, and deposit the sediment.

(2) It is now thought that the earthquakes which occur along the zone dipping about 45° are produced by one plate of Earth's crust pushing under the adjacent plate. Earthquakes are produced as the plates move.

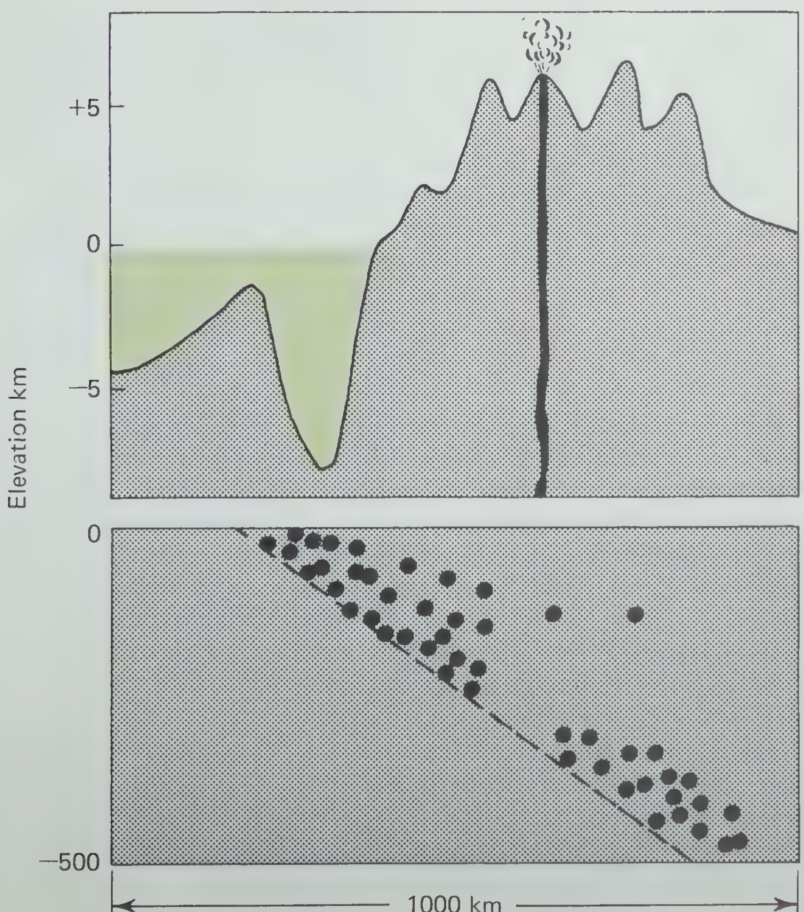


Figure 10.10 The type of contintental margin shown here is type B of Figure 10.8, but the ocean is to the left and the continent is to the right.

One other thing that we know about the trenches is that Earth's gravitational attraction is generally much less in these areas. This low gravity, together with the earthquake activity and the volcanoes, have made the trench areas some of the most puzzling of all to geologists and geophysicists. It wasn't until the late 1960s that we began to understand them (we think). In the 1960s, the theory of **continental drift** became generally accepted. This theory explains most of the major features of the ocean basins. Before we go into this theory, you might take a crack at developing your own scheme to explain the mid-ocean ridges, the fracture zones, and the deep-sea trenches.

CHECK YOUR FACTS

1. How do features of the ocean floor compare in size with land features?
2. How might submarine valleys be formed?
3. How are abyssal plains formed?
4. What are some characteristics of rift valleys?
5. What are some characteristics of deep-sea trenches?

(1)(1) **ANSWERS** / Check Your Facts

1. The major features of the ocean floor are generally larger than the major features of the continents because the ocean features are essentially features of Earth's mantle (not the crust) and because they are not obscured by erosion and deposition as much as are the features appearing on the continents.
2. Normal river erosion, creep of sediments, and turbidity currents.
3. Sediments dumped by turbidity currents fill irregularities in the ocean bottoms and thus form the abyssal plains.
4. Rift valleys are deep valleys that run along the length of mid-ocean ridges. They may have flat floors or irregular floors characterized by volcanic rocks. They represent the sites of many earthquakes and of relatively high flow of heat from the floor of the ocean.
5. Deep-sea trenches are long, linear depressions on the sea floor, generally but not always near the margins of the Pacific Ocean. They are hundreds of kilometers long, tens of kilometers wide, and several kilometers deep. They are characterized by associated volcanic action as well as by high earthquake activity. Earth's gravitational attraction is generally much less in these areas.

SEA-FLOOR SPREADING AND CONTINENTAL DRIFT

The theory of continental drift states that the continents have moved over Earth's surface. It has been one of the most controversial theories in the history of geology. At scientific meet ings some geologists, who are otherwise calm human beings, stand up trembling and red-faced and shake their fists at their colleagues, calling the theory of continental drift utterly idiotic. In the early days, most of the geologists in favor of continental drift were from the Southern Hemisphere—South America, South Africa, and Australia. It was in these areas that there appeared to be evidence that the continents had actually moved apart. The close fit of the east coast of South America with the west coast of Africa suggested that these continents were part of one large continent that had broken into pieces. Similarities in the kinds of rocks, the deposits of large continental glaciers, and the same kind of land fossils suggested to

some that South America, Africa, India, and Australia were at one time all part of a large continent. Geologists from these areas were convinced that continental drift must have occurred. Geologists from other parts of the world were troubled by how drift of large continents could occur. What the forces must have been bothered them. In short, the whole idea was inconceivable. Today most earth scientists (there are still a few hold-outs) believe that pieces of Earth's crust are in motion—that pieces of crust, including ocean floors, are moving at this very moment. In some places these pieces are moving apart, in other places together. Although a number of names have been given to these theories, they all involve **sea-floor spreading.**

The magnetic field and its flip-flops. As is frequently the case in science, evidence produced by a new technique may be the key to the solution of old problems. For continental drift and the origin of the major features of Earth's surface, it has been the measurement of Earth's magnetic field and the magnetic field preserved in rocks that has served as this key.

Many of the minerals in rocks react to magnetic forces. The lodestones used in the Middle Ages as natural compasses are a good example. They were made of the mineral *magnetite*. Magnetite, like the steel needle of a compass, responds to the Earth's magnetic field. Magnetite and other minerals like it form as molten rock cools. As they cool past a certain temperature they preserve in themselves evidence of the direction of Earth's magnetic field at that time. Extremely sensitive instruments are able to measure this preserved magnetic field millions of years after the minerals have formed. Thus, rocks with magnetic minerals in them are able to tell us something about the magnetic field through geologic time. We now know that over the past several hundred million years, Earth's magnetic field has completely reversed itself many times. The north magnetic pole has changed to a south magnetic pole, and then back to a north magnetic pole repeatedly over geologic time. The south magnetic pole has made corresponding reversals.

Measurements that led to this knowledge of magnetic reversals were made in the late 1950s in the northeastern Pacific Ocean and in the northern Atlantic Ocean. Surveys made at those times revealed that the magnetism of the rocks of the sea floor showed variations in long strips (Figure 10.11).

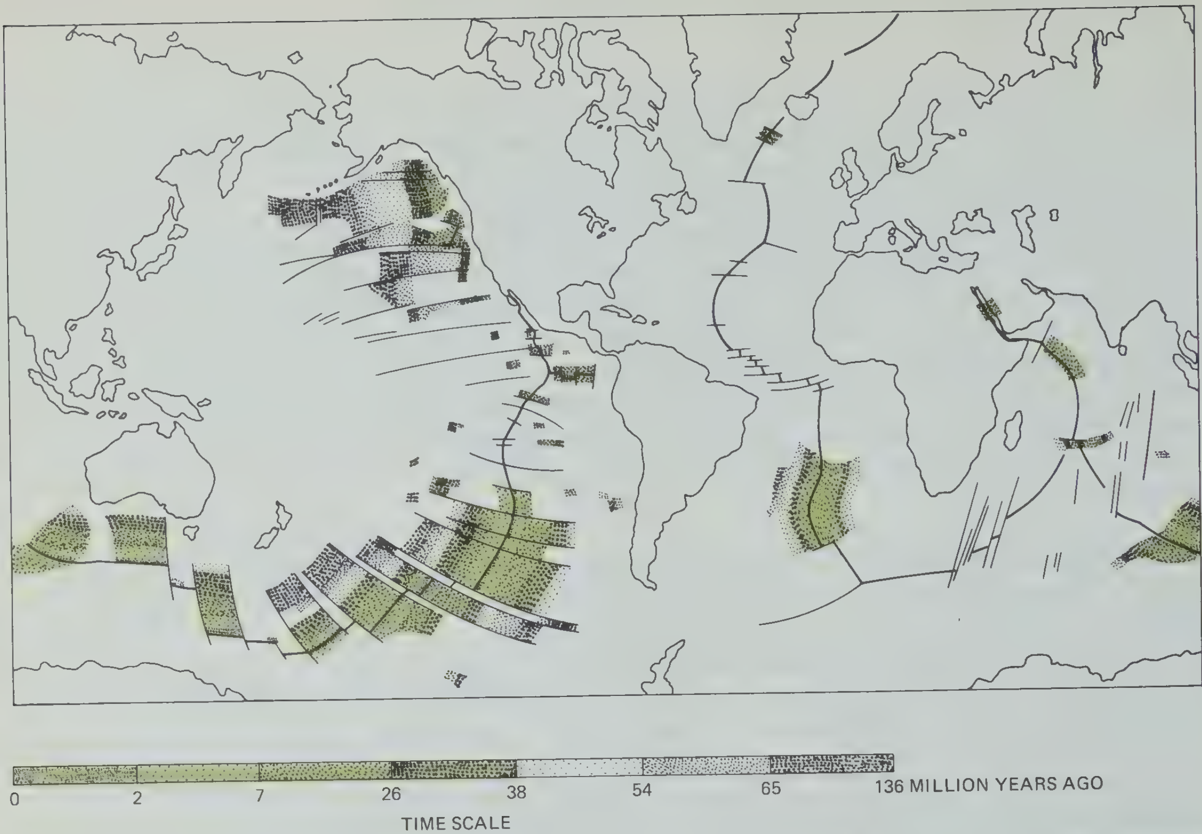


Figure 10.11 The different bands represent rocks of different ages. The magnetic reversal strips resemble these bands (they, too, lie parallel to the mid-ocean ridges), except that there are many more of them. For example, in the last 7 million years, there have been more than 20 magnetic reversals.

In the north Atlantic these strips are parallel to the Mid-Atlantic ridge. The patterns were similar on either side of the ridge. These patterns were due to normal and reversed magnetic fields preserved in the rocks. (By "normal" we mean the present magnetic fields.) Similar patterns of alternating normal and reversed magnetic fields were discovered in layered volcanic rocks on land. From the rocks on land it was possible by means of age-dating techniques to determine a precise age for each reversal of the magnetic field.

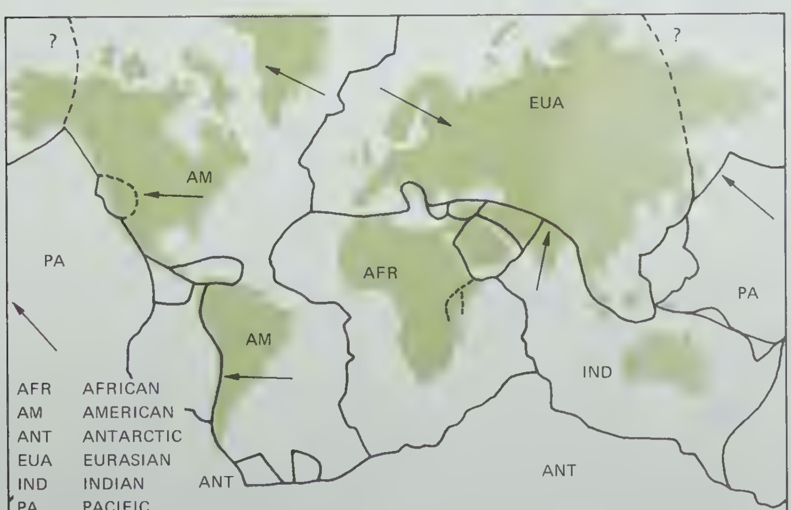
You can imagine how mystifying all of this was to geologists who were trying to tie these facts together. Finally the concept of sea-floor spreading was hit on. In general, the concept of sea-floor spreading calls for (1) formation of new crust at the center of mid-ocean ridges, and (2) movement of the sea floor away from the ridges to make room for new material to rise, cool, and form more crust. The movement of molten rock to the surface at the center of the ridge accounts for the higher heat flow in the rift valleys of the ridges. But what must be happening to the size of Earth if we add new crust at the centers of the oceans? Do you know of any evidence **(1)**

(1) If new crust is added at the centers of the oceans and nothing happens to the old crust, then the earth must be growing in size. There is no evidence that this is true; therefore, we must look for some way of destroying older crust. The text follows up on these questions.

that Earth is getting larger or smaller? If Earth is maintaining its present size, what must be happening to the crust? If you have suggested that the crust is being destroyed at about the same rate it is being formed, you are in agreement with a good many geologists and geophysicists today. Where do you suppose it is being destroyed? The general concept of sea-floor spreading calls for the formation of new crust at the mid-ocean ridges and the destruction of this crust in the deep-sea trenches. It is believed that Earth's crust consists of several large blocks that are moving away from each other, toward each other, and alongside each other (Figure 10.12). New crust is formed where the blocks move away from each other. It is destroyed where they come together. The trenches are the areas of collision and the mid-ocean ridges are where the blocks move apart. The fracture zones and major faults of Earth's surface are where the plates or blocks are moving alongside each other.

By this concept, can you explain the distribution of earthquakes (2) in Earth's crust? What might you say about the relative age of rocks as you move away from the mid-ocean ridges toward the shores of the oceans? Where would you look for the oldest rocks in the oceans? Can the magnetic patterns in the oceans be used to tell us anything about the rate of movement of the sea floor? (3)

Figure 10.12 Large blocks (also called plates) of Earth's crust are moving in the directions indicated by the arrows.



(2) The major earthquakes of Earth occur where large crustal plates are slipping past each other, or where one plate is riding over the top of another. The latter occurs in the area of the deep-sea trenches. The newest crustal material is formed at the mid-ocean ridges and, therefore, rocks which are at some distance from the crest of the ridges are older. The farther one goes from the crest of the ridges, the older the rocks become. Thus, one would look for the oldest rocks in the Atlantic, for example, close to the continental areas. The oldest rocks in the Atlantic have been sampled by the Deep Sea Drilling Project in an area close to North America. The same general concept pertains to the Pacific. In the Pacific the oldest rocks are found in the far western Pacific. The magnetic patterns are used to tell us something about the rate of movement, as explained further in the text.

(3) Some geologists have suggested that one practical use for the ocean floor resulting from our knowledge of sea floor spreading is to dispose of refuse. They suggest that inasmuch as one plate is being thrust under another at the areas of deep-sea trenches, we might dispose of refuse by dumping it in the trenches. It would eventually, therefore, become swept under an adjacent plate in a method analagous to sweeping dirt under the carpet. Eventually, it would be re-incorporated into the crust.

Because it has been possible to date the magnetic reversals, we can now use the position of the magnetic patterns and their distance from the mid-ocean ridges to compute the rate of sea-floor spreading. From this type of calculation it appears that spreading is highest in the southeast Pacific, about 15 to 20 centimeters per year. In the Atlantic it is somewhat slower, on the order of 2 to 5 centimeters per year. How much farther would Columbus's trip have been had he made it this year rather than in 1492? If we go backward in time, it becomes obvious that South America and Africa, Europe and North America must have been adjacent to one another at one time (Figure 10.13). How long ago would this have been? Can you think of any ways the concept of sea-floor spreading might be tested?

Figure 10.13 With the help of a computer, one oceanographer put together this map showing how continents fitted together.

Drilling holes in the ocean. An attempt to test this hypothesis and to learn more about the floor of the ocean was begun in 1968. A project, called the Deep Sea Drilling Project, was designed to drill deep holes in the floor of the ocean and to recover samples of the sediment and rock from these holes. In its early stages a number of holes were drilled in the Atlantic and Pacific Oceans. In the Atlantic, a series of holes was drilled both along the margins of the ocean and in several lines across the mid-Atlantic Ridge. It was reasoned that if sea-floor spreading were a fact, sediments resting on the oceanic crust should become progressively older the farther you went from the center of the ridge. The age of the sediments resting on the volcanic rocks of the crust should also give evidence as to the accuracy of the use of magnetic reversal strips for determining the age of the rocks. Rock samples collected from the holes drilled in lines across the Mid-Atlantic Ridge confirmed both assumptions to almost 100 percent accuracy. Sediment collected from right above the oceanic crust in holes drilled close to North America included abundant shallow water fossils about 180 million years old. What do these shallow water fossils suggest to you? To the geologists and geophysicists of the Deep Sea Drilling Project they suggested that Europe and North America were almost next to each other at that time with only a shallow water sea between them. Thus, the continents of Europe and North America began to separate and move apart 180 to 200 million years ago. Figure 10.14 shows how the continents have moved from that time to the present.

If the process of sea-floor spreading is an active one, we should find examples of it in early stages of development. The Red Sea appears to be just such an early stage in the development of sea-floor spreading. It is an area where continents have actually cracked apart and new ocean floor is beginning to form. Many of the features of the Red Sea are much the same as those occurring at the center of the mid-ocean ridges. The central trough in the Red Sea has characteristics common to rift valleys of the mid-ocean ridges. The parallel magnetic strips are there, the earthquakes occur in that area, and there is high heat flow. Oceanographic exploration of the Red Sea has revealed another very interesting feature. In the center of the Red Sea there are sediments and rocks that are very rich in metallic deposits. These include vast amounts of copper and zinc. These metallic deposits are probably brought to the sea floor by the rising molten rock

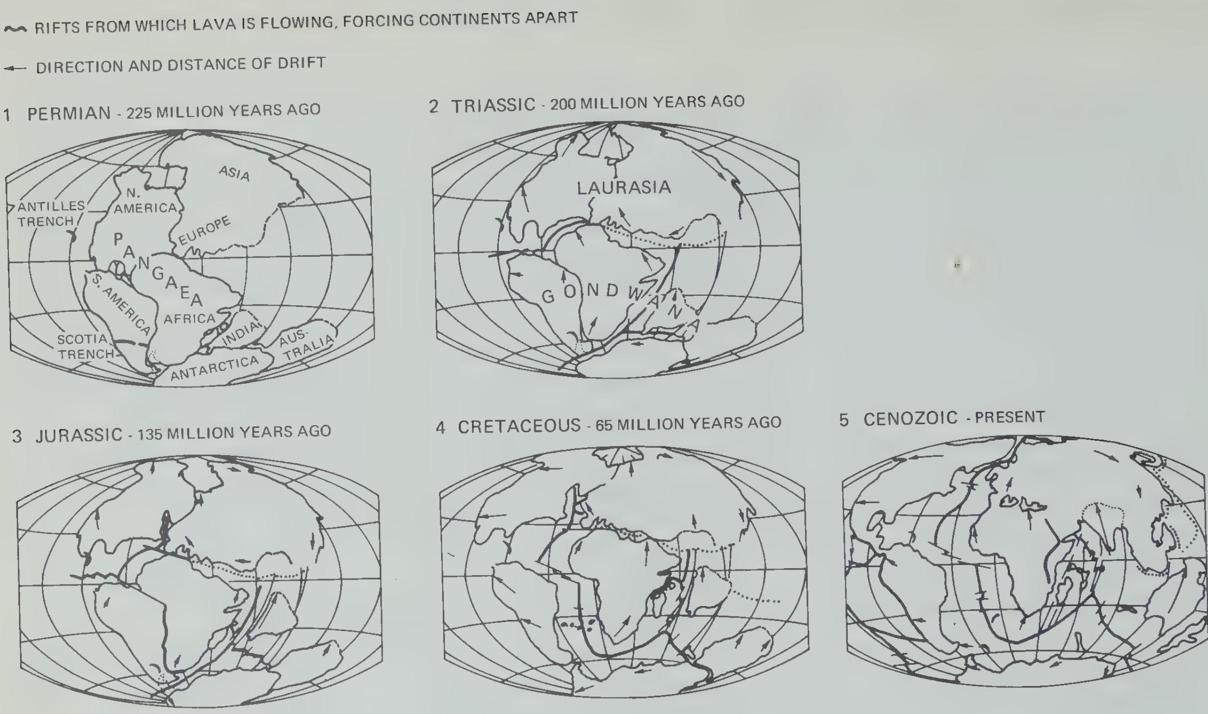


Figure 10.14 "Pangaea," "Laurasia," and "Gondwana" are names of land masses that have since broken up into smaller blocks.

that forms the crust. If these deposits form in the Red Sea, they may also form in other mid-ocean rifts and might be carried away from the rifts as the sea floor spreads. As a matter of fact, metallic deposits have been found in samples collected by the Deep Sea Drilling Project. In sediments collected from right above the oceanic crust near North America, substantial amounts of zinc, manganese, iron, and copper were present. Some day we may be mining deposits like these from the sea floor. Can you think of any other practical uses for the ocean floor resulting from our knowledge of sea-floor spreading?

CHECK YOUR FACTS

1. In what part of the world was the theory of continental drift first accepted?

2. How did scientists discover that Earth's magnetic field has reversed itself many times?

3. Where is new crust being produced? Where is crust being destroyed?

4. Where is the rate of sea-floor spreading the greatest?

(1) ANSWERS / Check Your Facts

1. The theory of continental drift was first accepted by Southern Hemisphere geologists because of the abundance of readily observable geological evidence supporting it.
2. Reversals in Earth's magnetic field, as observed in ancient rocks, was first discovered by using magnetometers at sea. Surveys made in the northeastern Pacific revealed that the magnetic field preserved by the rocks occurred in long,
(1) linear strips of high magnetic and low magnetic strains. Similar reversals in the magnetic field were discovered in rocks on land which were subsequently dated by the use of isotopic methods.
3. Geologists and geophysicists believe that new crust is being added in the rift valleys at the centers of the mid-ocean ridges and is being destroyed where one plate encounters another at the deep-sea trenches.
4. On the basis of the position and age of magnetic lineation, it has been estimated that the fastest rate of sea floor spreading occurs in the southeast Pacific.

APPLYING WHAT YOU HAVE LEARNED (2)

1. During the Ice Ages continental glaciers increased in size and then decreased in size by melting. What would be the effect on the shape of the oceans if the present continental glaciers doubled in size? What would be the effect if the glaciers melted? Be as detailed as you can.

2. We often hear of the ocean "basins." Are the oceans really shaped like basins? If you had a model of the ocean the size of a basketball, what would be the shape of the body of water representing the ocean? On a model the size of a basketball, how deep would the water be?

3. Sound travels through seawater at about 1500 meters per second. If a pulse of sound returns to our echo sounder 6 seconds after it is sent, how deep is the water?

4. Turbidity currents may be at least in part responsible for submarine canyons and abyssal plains. What would you expect the sediment deposited by a turbidity current to be like?

5. How would you expect a deep-sea trench half filled with sediment to differ from one that had no sediment in it? How might you account for the difference in amount of sediment?

6. As our coastal areas become more and more crowded, it may be necessary to build islands out on the continental shelf to use for airports, power plants, and shipping centers. What are some of the problems we will need to solve before we can build such islands on the continental shelf? Do you think we will ever build underwater cities out on the shelf? Why?

KEY WORDS

echo sounder (p. 215)
continental rise (p. 217)
submarine valley (p. 218)
submarine canyon (p. 218)
deep-sea plain (p. 220)
abyssal plain (p. 220)
seamount (p. 221)
rift valley (p. 221)
fracture zone (p. 222)
deep-sea trench (p. 222)
continental drift (p. 224)
sea-floor spreading (p. 225)

(2) **ANSWERS** / Applying What You Have Learned

1. If the glaciers doubled in size, the sea level would drop below the edge of the continental shelf. If the glaciers melted, the sea would rise 100 to 300 meters. A contour map would show this. Answers may go on from here.
2. The shape of the ocean would be convex, following the shape of the basketball. The depth of the water would be what remained on the ball after the water was shaken off (less than 1 mm).
3. The sound would travel 3 sec at 1,500 m/sec to the bottom—the depth of the water is 4,500 m.
4. A graded bed.
5. The former would have a flat bottom; the bottom of the latter would be V-shaped. The lack of sediment might be accounted for by the proximity of sources of sediment or of marginal basins that are sediment traps. If the trench were at the border of two plates, the movement of the plates would scrape off the sediment.
6. This is an open-ended question designed for class discussion.

Figure 11.1 Sunlight, sea, clouds, atmosphere—all are related, as you will learn in the following chapters.

Introductory Demonstration

A simple demonstration involving the electrical conductivity of sea water can be set up using a power source, light bulb or ammeter, and a beaker of salt water (as part of the conductor). As the salinity of the water is increased, the light bulb should burn more brightly or the ammeter should show a greater flow of current.

chapter 11

The Dynamic Seas

If someone asked you what parts of Earth are most important to your environment, you would probably say the land and the atmosphere. You live on the surface of the land, at the bottom of the immense atmosphere. Therefore, these are the most important parts of your environment.

But you might be wrong. What about the ocean? "But I don't live in the ocean," you might reply. True, you don't live in the ocean, but the ocean is vitally important to you. For example, have you heard of **phytoplankton**? Phytoplankton is made up of microscopic plants that live in the upper layers of the ocean and produce oxygen. (This process, called photosynthesis, will be discussed in the next chapter.) Much of the oxygen in the air that you breathe came from phytoplankton in the ocean. This is just one example of how important the oceans are, even though you don't live in them.

Oxygen produced in the ocean passes into the atmosphere, but some oxygen in the atmosphere also becomes dissolved

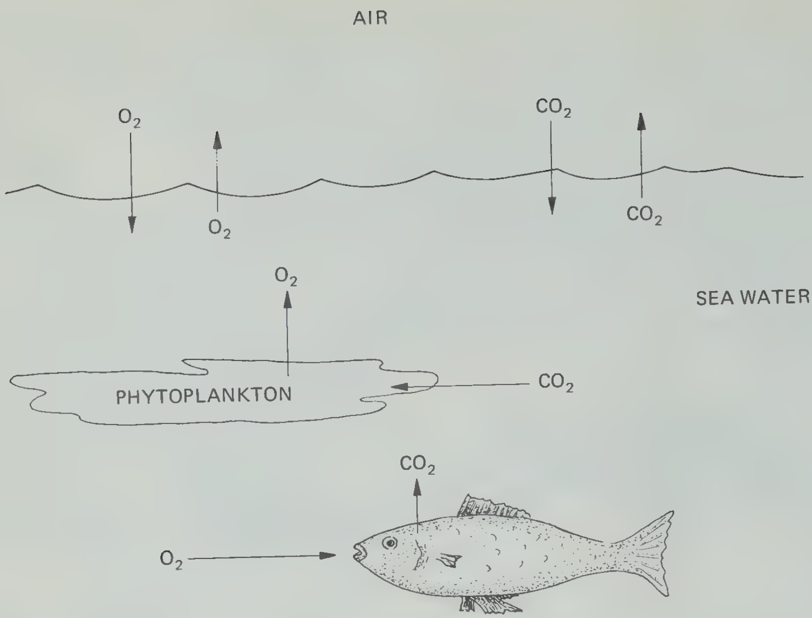


Figure 11.2 Many scientists are afraid that one day pollution will kill the phytoplankton. What would happen to us then? (1)

(1) We would suffer severely from lack of oxygen.

in the ocean. And other gases, particularly carbon dioxide, are also exchanged between the ocean and the atmosphere (Figure 11.2). (2)

(2) Dissolved gases in water are also affected by the temperature and salinity of the water. As the temperature increases and also as the salinity increases, the amount of gas which can be dissolved in water decreases. More gas can be dissolved in cold, fresh water than can be dissolved in warm, salty water. A very simple demonstration of the effect of salt or heat on a liquid containing dissolved gases can be done with a bottle of soda pop. Fill a beaker or glass with soda pop and dump in a large quantity of salt. The carbon dioxide which gives the pop its fizz will immediately be forced out of solution with dramatic results. Alternatively, as a glass of pop stands and warms under room temperature, bubbles will constantly rise to the surface until all the dissolved carbon dioxide has been forced out.

THE OCEANS AND THE ATMOSPHERE—AN INTIMATE AFFAIR

In a sense, the ocean and the atmosphere are parts of the same system. Materials present in one are present in the other—though of course in different proportions and, in some cases, in different states (solid, liquid, or gaseous). We have already mentioned the exchange of gases between the atmosphere and the ocean; later we will see that water itself is exchanged, as is salt. In addition to the transfer of matter across the air–sea boundary, there is also a transfer of energy, both radiant and mechanical. The most obvious example of transfer of mechanical energy is when wind (movement of the atmosphere) produces waves and currents (movement of the water). Let's take a look at currents.

Currents. Since the days of Benjamin Franklin (1706-1790), attempts have been made to map the major ocean currents to help speed ships on their way from one point to another across the ocean. One of the earliest maps of the Gulf (3) Stream was published by Benjamin Franklin. It was his hope that knowledge of this important current would help to speed

(3) Although our understanding of the processes affecting the Gulf Stream and other major currents is well developed, there is still much that we do not know. It should be obvious from the diagrams of the Gulf Stream that this current meanders and may in fact even break off as pods of relatively warm water. A detailed knowledge of the meanders of the Gulf Stream can be of some advantage to those involved in commerce on the high seas. Although Benjamin Franklin's map of the Gulf Stream was very

up mail service between England and the American colonies. In the middle 1800s an American naval officer, Matthew Maury, produced a much more detailed map of currents of all the major ocean basins. Maury's map was based on observations of U.S. Navy ships from all over the world. By putting together a great number of observations, modern oceanographers have come up with a fairly accurate circulation pattern for the world oceans (Figure 11.3).

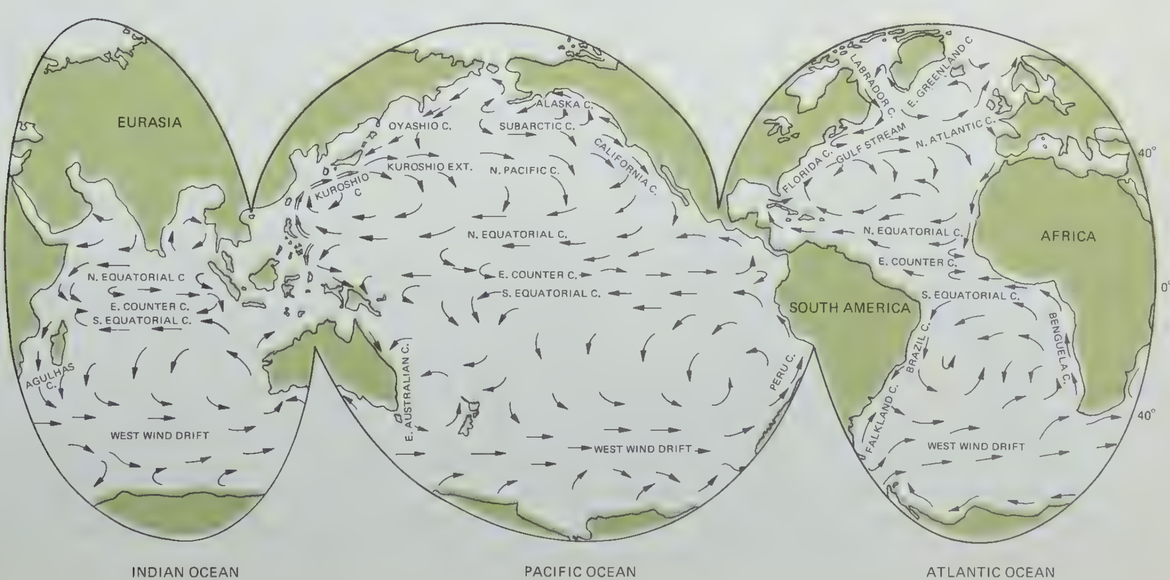
Do you see any similarities between the various currents shown in Figure 11.3? How does the circulation of currents in the Northern Hemisphere differ from that in the Southern Hemisphere?

Walter Munk, a well-known American oceanographer, has attempted to show systematically why the currents in various oceans are similar. This system is shown in Figure 11.4 by an idealized, rectangular ocean in which Earth's wind system is also shown. Notice the circular current patterns, or **gyres**, in the idealized ocean. The gyres rotate clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Do you see the same gyres in the real oceans (Figure 11.3)?

Because of the irregular distribution of land masses, the real oceans are, of course, different from the rectangular idealized ocean, but also remarkably similar. In general, currents are strongest in the western parts of the ocean and are somewhat slower in the east. Strong winds in the vicinity

crude, it did prove a definite asset to those carrying mail between the American Colonies and the British Isles. A knowledge of the location of the Gulf Stream allowed ships sailing from west to east to take advantage of its velocity. Even today, men racing sailboats from New England to Bermuda try to encounter a meander moving from north to south to take advantage of the velocity toward Bermuda. These types of details were, of course, unknown at the time of Benjamin Franklin.

Figure 11.3 Surface currents of the world's oceans are shown on this map.



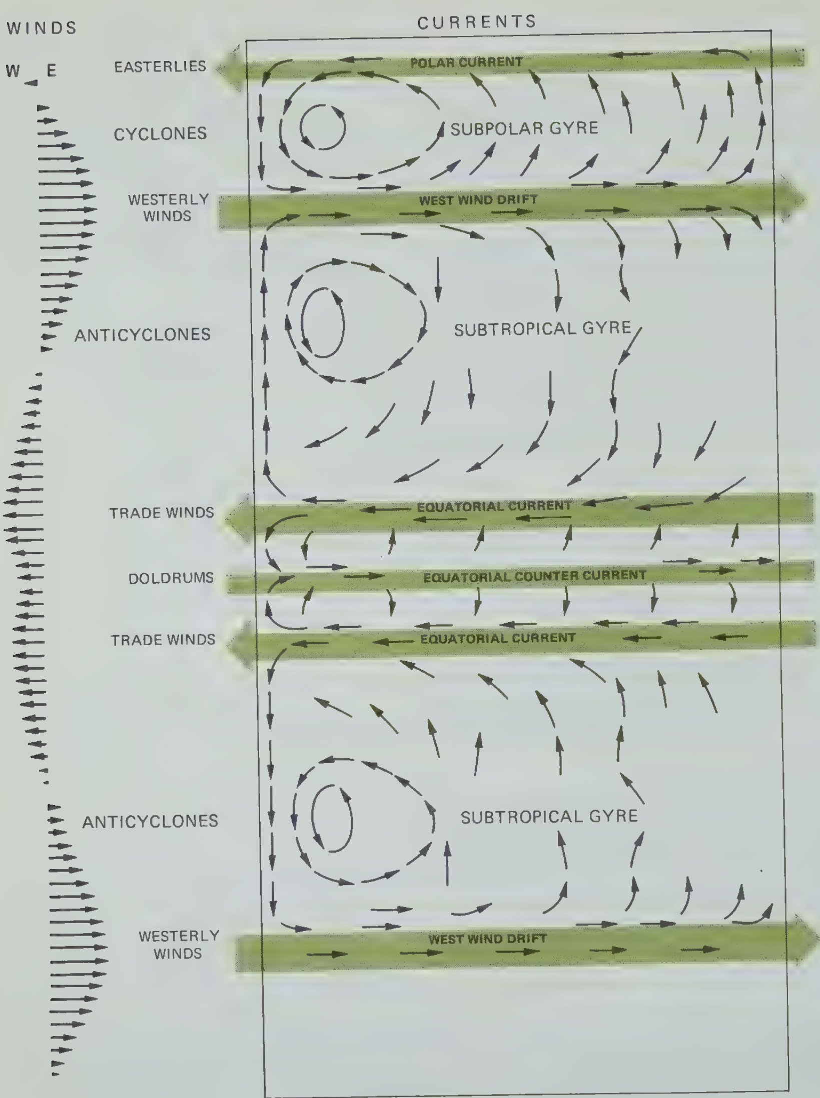


Figure 11.4 The arrows at left indicate the general wind pattern of the world. Their length indicates the strength of the wind. The "doldrums" refer to the areas along the equator where winds are weak or even absent. The westerly winds, or westerlies, blow strongly along latitudes 40° to 50° north and south. As you can see, the wind and ocean current patterns are closely related.

of 40°S latitude drive the currents completely around Earth. What type of current patterns might you expect to find on Earth if there were no continents to serve as barriers?

Exactly how the wind moves the water is not known. It may be that friction is important as the wind slides over the surface of the water, or it may be that the wind exerts pressure on waves as it blows across the rough surface of the sea. However it happens, the wind does move the water in large masses across the ocean. The gyres are undoubtedly the result of ocean barriers and systematic winds that are not of equal force or in the same direction. Couple these factors with Earth's rotation, and the circular pattern can be explained.

(1)(1) If there were no continents to serve as barriers to currents, we would have currents which swept around the globe in response to the wind patterns. Obviously, some zones of shear would develop which would create areas of some turbulence between the wind-driven currents. Give your students free rein in developing this idea. You may wish to expand on their thinking by inserting into a map imaginary continents of different shapes and positions in order to test their understanding of current processes.

Water from the deep. The transfer of energy from the atmosphere to the ocean by the winds directly affects the surface currents. Frequently, however, it also affects the movement of water at depth. Fridtjof Nansen, a Norwegian oceanographer, noted in the Arctic that when the wind was at his back, small ice floes were not moving directly away from him but were moving off to his right. The motion of the ice to the right of the wind is caused by Earth's rotation. In the Northern Hemisphere movement is to the right of the wind; in the Southern Hemisphere, to the left of the wind. This movement of water or wind resulting from Earth's rotation is called the **Coriolis effect**.

activity 11.1 The Coriolis effect

For this activity you will not need any equipment. You'll need only your imagination.

Imagine that you are a tiny creature standing at the center of a record on a record player. You fire a pistol in any horizontal direction. What is the path of the bullet over the record? It is of course a straight line going directly from the center of the record to the edge of the record and out beyond it. That was simple, wasn't it?

Now suppose someone starts the record player spinning. You again fire your pistol. As the bullet leaves the center, the record is no longer standing still under it, but is moving toward the right.

Now what is the path of the bullet over the record? If it cut a continuous scratch on the record as it traveled from the center to the edge, what shape would the scratch be? Is it a straight line from the center of the record to the edge, or does it veer to the side? To which side—left or right? Suppose the center of the record, where you are standing, is one of Earth's poles. Which pole would it be—the North Pole or the South Pole?

It can be shown that the veering effect takes place not just in the case we've described—shooting a projectile from a pole. If you shoot a projectile *anywhere* on Earth, it veers to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere. It acts as though it were being pushed sideways. This apparent push is what is called the Coriolis effect. Winds, currents, and all other objects moving over the globe are subject to the Coriolis effect.

Along the western margins of continents, where winds blow parallel to shore and toward the equator, the surface water is moved offshore because of the Coriolis effect. The surface water is actually skimmed off the surface near shore and is piled up offshore. However, it is impossible for the wind to blow a "hole" in the ocean for very long before that hole is replaced by other water. The "hole" formed when the near-shore water is moved offshore is rapidly "filled" by water from below, which is both colder and saltier than the surface water. (Why is the water below saltier?) This water from below also has a higher content of chemicals which serve as fertilizers for the phytoplankton, allowing them to grow more rapidly. This upward movement of water is called **upwelling**. What effects might you expect upwelling to have on the distribution of fog, conditions for swimming, and local fishing? (1)

Water masses. The masses of water moved by winds develop certain physical characteristics during the time they are in contact with the atmosphere. The temperatures of these waters are, to a great extent, determined by the temperature of the air moving them. The amount of evaporation and rainfall in the area determine the **salinity** (degree of saltiness) of the water. Where waters that are moved by different currents meet each other, (such as in the Grand Banks area off Siberia) the colder, saltier, heavier water sinks beneath the lighter, warmer, less salty water. In this way, **subsurface water masses** are developed. Although the subsurface movement of water masses is less well known than the movement of surface water currents, oceanographers do know that water from the high latitudes may move as subsurface masses toward the equator, and in some cases across the equator, at a slow rate in all the ocean basins.

The Mediterranean Sea gives us a good example of how the atmosphere affects the properties of a surface water mass that eventually becomes a subsurface water mass. In the hot, dry eastern end of the Mediterranean, evaporation of water is very rapid. The extreme evaporation in the area results in high salinity (Figure 11.5). Because of its high salinity, this water becomes relatively heavy and sinks beneath the surface. It flows on or near the bottom along the coast of North Africa and eventually out through the Straits of Gibraltar. Because it is more dense than the Atlantic water directly outside the Straits of Gibraltar, it sinks to a level where the water below is heavier and the water above lighter. At this depth it spreads (2)

(1) In the oceans, water below the surface is generally colder and saltier than the water at the surface. It also contains a higher content of nitrate and phosphate. During periods of intense upwelling, this water is brought to the surface. Because it is very cold it tends to cool the air directly over the ocean. This results in condensation of atmospheric moisture which produces heavy fog. For swimming, upwelled water is usually much too cold. Ordinarily fishing is good in areas of upwelling. This is generally due to the fact that the upwelled waters are high in phosphate and nitrate, which serves as fertilizer for the phytoplankton or small plants in the surface waters. These plants grow much more rapidly when they are fertilized and thus provide a more luxuriant base for the entire food cycle. The phytoplankton are eaten by small floating animals, the zooplankton, and these in turn serve as food for fish. All of this results in larger fish populations and better fishing.

(2) The Mediterranean provides one of the best examples of vertical circulation patterns developed by atmospheric conditions. Other areas where similar patterns may develop can be found in areas of high evaporation, such as the Red Sea and the Persian Gulf. Basins of similar shape located in areas of high precipitation rather than evaporation do not develop this type of vertical circulation due to the fact that the fresh water added through precipitation and runoff serves as a light layer at the surface. These basins are well stratified, with heavy (salt) water below and relatively fresh water at the surface. In basins such as the Mediterranean and Red Sea where vertical circulation is developed, the salinity, temperature, and dissolved oxygen frequently serve as indicators which make it possible to trace the movement of water. The temperature-salinity characteristics are developed near the surface and can be followed at depth. Because the characteristics of the water were originally affected at the surface, the oxygen content is fairly high. Although some of this oxygen will be used up by animals living in the water, the amount of oxygen will still be fairly high even though the water has moved some distance in the subsurface.

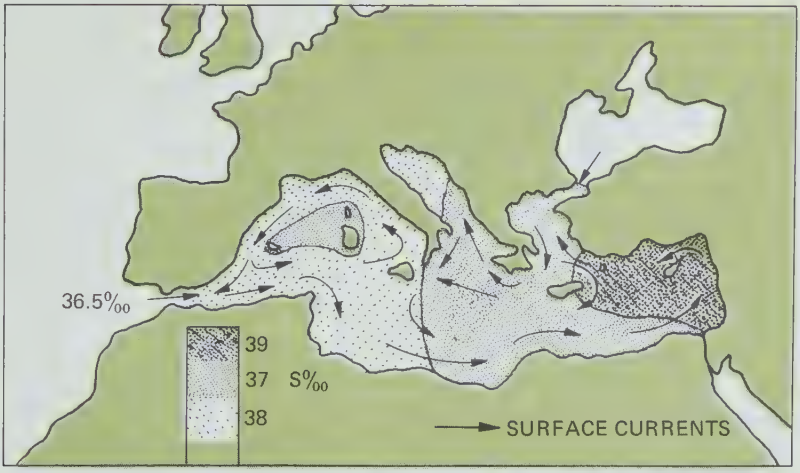


Figure 11.5 The values shown refer to salinity. The higher the value, the higher the salinity. (The symbol ‰ means "parts per thousand." For example, 36.5 ‰ means 36.5 grams of salt per thousand grams of water.) The arrows represent surface currents.

out horizontally into the North Atlantic. As replacement for this subsurface water that has left the Mediterranean, surface water flows into the Mediterranean through the Straits of Gibraltar. Thus, at the Straits of Gibraltar, water flows into the Mediterranean at the surface and out along the bottom. This in–out flow at the Straits of Gibraltar is due to the general vertical movement of waters originally caused by the climatic conditions in the eastern Mediterranean. Can you think of other examples where such vertical circulation patterns might develop? What characteristics would you look for in the surface and subsurface waters to determine whether such circulation exists?

CHECK YOUR FACTS

1. Name one way in which the oceans are important to your environment.

2. What is a general difference between the circulation of ocean currents in the Northern Hemisphere and that in the Southern Hemisphere?

3. What effect does upwelling have on phytoplankton?

4. What is the pattern of flow at the Straits of Gibraltar?

(3) (3) **ANSWERS** / Check Your Facts

1. Phytoplankton in the ocean produces much of the oxygen we need.
2. Direction of flow: the gyres flow clockwise in the Northern Hemisphere, counterclockwise in the Southern Hemisphere.
3. It constantly renews the mineral supply (fertilizer) of the plankton.
4. In general the flow at the Straits of Gibraltar is into the Mediterranean at the surface, and out of the Mediterranean along the bottom.

EARTH'S THERMOSTAT

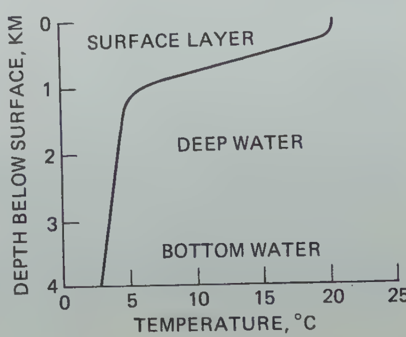
Without the ocean, Earth would be an impossible place to live. At the equator temperatures would be much too high for life to survive, and in higher latitudes everything would be frozen solid. Luckily, the oceans serve as a thermostat, and because so much of Earth's surface is covered by water it is possible for man to survive at all latitudes.

The oceans serve as Earth's thermostat for two reasons: (1) because it's possible for water to absorb or give up a great deal of heat without changing its temperature very much, and (2) because the ocean currents carry water from low latitudes to high latitudes and back to low latitudes. Thus, much of the heat energy that strikes Earth near the equator is absorbed by the ocean, carried by currents to colder areas where heat is lost to the atmosphere, and the cooled-off water is brought back down to the equatorial regions where more heat energy is put back into it. This type of thermostat works on a yearly time scale.

The oceans act as a thermostat on a daily basis also. They receive solar energy during the day and are warmed up; and they radiate much of this energy back to the atmosphere at night, when other areas of Earth are receiving the Sun's energy. Although some of the heat gained by the ocean during the day is lost at night, not all of it is. Waters in equatorial regions generally heat up little by little, day by day, as they move westward across the oceans. As the currents sweep away from the equator toward the poles, in the western parts of the oceans, they gradually give up their heat. It has been estimated that if the oceans retained all of the heat produced by the absorption of solar energy, they would boil in about 300 years. Obviously, this isn't happening; in fact, it appears that there has been relatively little change of ocean temperature through geologic time. This means that the energy received by the oceans is eventually given back. There is no net gain of heat and no net loss. The heat budget for the ocean is balanced. Incoming energy is balanced by energy lost.

The heat budget. Just about all of the energy that comes to the surface of the ocean is from the Sun. Although a certain amount of this energy is reflected from the water surface back into the atmosphere, much of it is absorbed in the upper part of the ocean. This is evident if we look at the distribution of temperature in the ocean (Figure 11.6). In most parts of

Figure 11.6 The temperature of sea water usually varies with depth in the manner shown here.



the ocean there is a layer of relatively warm water lying over the colder, deeper water. What does this mean in terms of the balance of heat gained and lost? In areas where a great deal of energy is added, the layer of warm water is relatively thick. In other areas where heat is being lost more rapidly, the layer of warm water is thin or even absent.

Almost all the heat that is added to the ocean by absorption of the Sun's radiation is returned to the atmosphere by three processes: (1) direct conduction of heat to the atmosphere, (2) radiation back into space, and (3) evaporation (Figure 11.7). Where the ocean is warmer than the overlying air, it transfers a small amount of heat by directly warming the air. A molecule of water directly transfers its energy or heat to an adjacent molecule of air. This is conduction. For the entire ocean this amounts to less than 10 percent of the heat lost.

Because the ocean surface is warmer than the atmosphere at different times and places, it *radiates* energy into the atmosphere. This process is particularly common at night. About 40 percent of the energy received by the oceans is lost by radiation back to space.

The remaining heat, about half of the ocean's total heat, is lost during the evaporation of surface water. As the temperature of the surface water increases, its molecules move more and more rapidly. When the motion is fast enough some of them break away from the water surface and escape into the overlying atmosphere. The water molecules that escape are those having higher energy; they are the warmer ones.

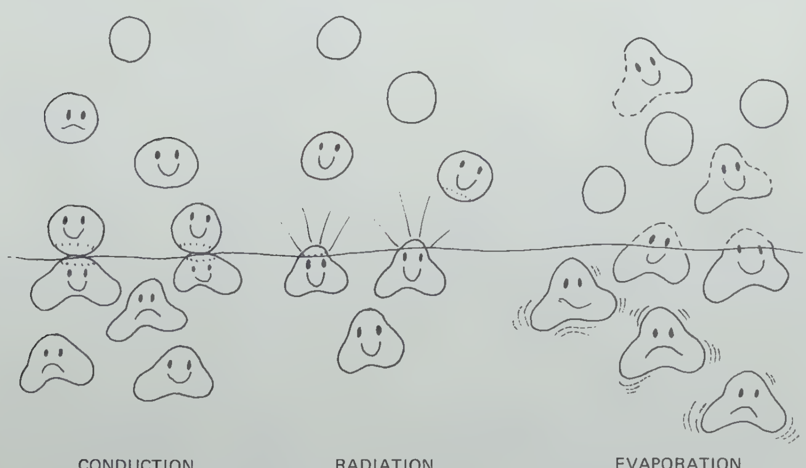


Figure 11.7 Energy is transferred from the ocean to the atmosphere by these processes.

Those molecules that remain behind are the relatively cool ones with less energy. Thus, the atmosphere is warmed and the oceans are cooled by the evaporative process. Do you know of any examples of how evaporation is used by man to take advantage of its cooling effect? (1)

The process of evaporation is a very important one, not only in keeping the oceans cool but in keeping the water cycle in operation. It is by evaporation that water vapor is transferred from the ocean to the atmosphere. Almost all of the water vapor in the atmosphere comes from the oceans.

As water evaporates from the ocean surface, it leaves behind the salt that was dissolved in it. The surface water becomes cooler, saltier, and therefore heavier. In its heavier condition it may become involved in vertical movements such as those that occur in the Mediterranean. Wind blowing "dry" air across the water surface speeds up the rate of evaporation. The wind also creates waves. If the wind blows hard enough, small droplets of water may be thrown directly into the atmosphere. These water droplets frequently evaporate before falling back into the ocean. When this happens, a very small crystal of salt is left in the air. These very small salt crystals frequently serve as the particles on which water vapor condenses to form rain. As this rain falls on the land, it carries the salt with it. Eventually the salt washes back into the ocean.

As long as the cycle is not interrupted, the oceans remain constant in volume, temperature, and salinity. During the recent geologic past, however, for reasons we do not completely understand, Earth's atmosphere cooled and much of the water that fell on Earth accumulated as snow and ice to form glaciers. The water was not returned to the sea. As evaporation continued, more and more water was trapped as glacial ice. The level of the sea dropped; the average temperature of the sea dropped; the oceans became saltier. Then, for some unknown reason, the average temperature of the atmosphere began to increase, the glaciers melted, and the water was returned to the ocean, causing sea level to rise. This interruption of the water cycle happened at least four times during the past 2 million years, resulting in four major Ice Ages. With each Ice Age, sea level dropped. With the melting of the glaciers, sea level rose. How do you suppose this rising and falling of sea level affected the sea floor and the shore line? How might it affect the ocean currents? Would you expect the lowered sea level to have any effect on geologic processes on the land? Are there any ways man might change the water cycle? How might these changes affect man's future on Earth? (2)

(1) Evaporation has been used for cooling for some time. Evaporative type air conditioners are common in hot areas of low humidity. Canteens and water bags make use of the evaporative process to cool the contained water.

(2) The rising and falling of sea level had considerable effect on the formation of the continental shelves. The surf zone moved seaward and then landward again and served to erode the area, thereby producing a relatively flat shelf. As sea level dropped, rivers discharging into the ocean caused deeper valleys; these were subsequently flooded as sea level rose. Some of these valleys have been filled with sediment; others now exist as submarine valleys beneath the sea surface. The change in shape of the ocean bottom during periods of lowered sea level must have had some influence on the currents, particularly in areas such as the Bering Sea and the North Atlantic.

There is a great deal of concern at the present time as to whether the discharge of pollutants in the atmosphere may create climatic changes which would affect the hydrologic cycle. Students might consider the problems created by the construction of major dams on the larger rivers of the world and their long-range effect on the hydrologic cycle. Obviously, any of these things will have a profound influence on man's future on earth. Let your students run with this one.

CHECK YOUR FACTS

1. Does the ocean retain all the heat it absorbs from the Sun?

2. Which level of the ocean is the warmest?

3. Which process accounts for about one half of the ocean's loss of heat?

APPLYING WHAT YOU HAVE LEARNED

1. Different salts are brought to the ocean by rivers from many different areas. We might expect that if we were to sample different parts of the ocean we would find different salts in the water. Not so. Out in the main part of the ocean where the sea is well mixed, the proportion of one major ion to another is always the same. Thus, the ratio of sodium ion to chloride ion is the same in the southern Indian Ocean as it is in the northern Atlantic. Can you think of a practical use for this knowledge of constant proportions?

2. Waters of the ocean are well mixed by wind-driven waves and by currents. The worldwide network of surface currents was well demonstrated several years ago. A float from a piece of oceanographic equipment was lost from an oceanographic research vessel in the North Pacific, south of the island of Adak in the Aleutians. Several years later this float washed ashore on a Spanish beach just inside the Straits of Gibraltar. On a chart of the world, trace the path this float must have traveled from where it was lost in the North Pacific to where it was found in the Mediterranean. How long would it have taken if the average current velocity was 5 km a day?

3. Currents may occur almost anywhere. The axis of rotation of the newly-discovered planet Weirdo is parallel to that of Earth. However, the Sun rises in the west and sets in the east. The planet has one continent and one ocean of equal size. The shoreline of the continent passes through both ends of the pole of rotation. Describe the surface currents pattern in Weirdo's ocean. On which side of the continent and under what conditions would upwelling occur? What other differences might you expect between Earth's ocean and Weirdo's?

KEY WORDS

phytoplankton (p. 233)
gyre (p. 235)
Coriolis effect (p. 237)
upwelling (p. 238)
salinity (p. 238)
subsurface water mass (p. 238)

(3) (3) **ANSWERS** / Check Your Facts

1. The ocean gives out about the same amount of heat as it absorbs from the Sun; thus, it is neither warming up nor cooling down. Naturally, it does not do this in the same place; it generally absorbs energy at low latitudes and releases energy at higher latitudes.
2. The surface waters of the ocean are warmest. They are the waters which recover the Sun's energy directly.
3. About half of the heat lost from the ocean is lost through the process of evaporation: 10% is lost through conduction directly to the atmosphere and 40% by back radiation.

(4) **ANSWERS** / Applying What You Have Learned

1. If you know the proportions, one analytical result will give the entire saline content.
2. The answers here will vary with the route chosen. Stress should be placed on the gyre systems in the Northern and Southern Hemispheres.
3. The Coriolis forces would be opposite in direction to those on Earth. This ocean would probably freeze at the poles. There would be no reverse gyres. Students might realize that this is actually a good model of the Pacific.

Figure 12.1 What is happening to our ocean of air? How long can we keep mistreating it like this?

Introductory Demonstration

List five atmospheric gases on the chalkboard in some such order: carbon dioxide, oxygen, nitrogen, water vapor, argon. Ask your class to arrange these gases in order of dominance in the atmosphere. Many will place oxygen first because they know it is essential to life. The misconception about the dominant gas provides a good point of departure. Next, arrange the gases according to percentage by volume: Argon is 0.93% and carbon dioxide 0.03%. For the moment, ignore water vapor. Point out how fortunate we are to have the inert gas nitrogen as number one. Otherwise we would oxidize or burn up. If time permits, have your students attempt to rearrange the gases in order of importance. This cannot be done. Aside from argon they are all important. A good discussion may well arise from this.

chapter 12

The Ocean of Air

If you were coming in toward Earth from outer space, one of the first things you would see would be big swirls of clouds. A closer look would tell you that these fleecy white streamers are always changing shape and position. They would seem to be drifting about in a kind of transparent sea. If this were your first trip to planet Earth, you might wonder what this "sea" is like. Then suddenly, before you had even completed your thoughts, its presence would become most obvious: The heat produced by the friction between it and your spaceship would completely burn up your ship—and you! Your story would end in a fiery streak very much like the passing of a "falling star."

But let us hope that instead your ship is properly shielded and shaped so that your story ends with a safe landing. But even so, you would know that this transparent envelope of air is very, very real, because of the sudden slow-down when your ship hit it. You would surely ask yourself: "What is this transparent mixture of gases that Earth men call their atmosphere?"

WHAT IS THE ATMOSPHERE?

Although we cannot see the gaseous mixture we call the atmosphere, it is as real as the rocks in the hills, the waters in the sea, and the food we eat. It is estimated that there are 5.7×10^{15} tons of it. We nibble slightly at this huge amount in our lifetimes; the rate of consumption is about 14 kilograms a day per person.

How do we depend on the atmosphere? The approximate composition of the atmosphere is shown in Table 12.1. This is a long list for something as common as air. And this list is not complete! Other gases must be added, such as (1) water vapor. And there are many solid substances that are scattered in the atmosphere in the form of small particles. We can see from the table that the atmosphere is about 78 percent nitrogen and 21 percent oxygen. This leaves a tiny one percent for all other materials. But remember the old saying—important things don't always come in big bundles. (2)

You already know how important oxygen is. You cannot live without it. What happens in your lungs when you breathe? What is happening in Figure 12.2? In order to live, you need energy. This energy is released to your body when glucose (a kind of sugar) from your body combines chemically with oxygen.

Any process in which living organisms obtain energy from their food is called **respiration**. This process we have described is one form of respiration and can be represented in this way:

(1) The obvious move here would be to explore the oxygen and nitrogen cycles. Both are essential to life but the consumption of oxygen is direct, whereas that of nitrogen is indirect. See *Scientific American,* September 1970, "Oxygen Cycle," by Preston Cloud and Aharon Gibor and "The Nitrogen Cycle" by C. C. Selwicke. Discuss other cycles in natural phenomena such as the hydrogen cycle, day and night, and winter and summer.

(2) Why so much nitrogen? A discussion of the history of the atmosphere should help with the answer. See *Scientific American,* August 1953, "Origin of the Atmosphere," by Helmut E. Landsberg.

Table 12.1 Composition of dry air collected from the lower part of the atmosphere **(3)**

Gas	Percentage by volume
nitrogen	78
oxygen	21
argon	
carbon dioxide	
neon	
helium	1
ozone	
hydrogen	
krypton	
xenon	
methane	

Figure 12.2 The patient is in an oxygen tent. How does the oxygen tent help him?

(3) Pose the question: Isn't water vapor an important atmospheric gas? Why has it been left out of Table 12.1? Now have your students read the caption of the table. The key words are *dry air.* Water vapor is a variable gas and is therefore omitted. The gas may range from almost nothing to 4%. Lead a discussion on the important and varied role of water vapor in the atmosphere. Cover the following factors: (a) precipitation; (b) storm energy; (c) sensible temperature—high humidity meaning high sensible temperature; (d) the "greenhouse effect" (Chapter 13).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

glucose oxygen carbon dioxide water

All living things need energy to keep the life processes going. And with a few exceptions, all living things need oxygen to enable them to get this energy.

You might think that carbon dioxide is not important, since you throw it away every time you breathe out. But carbon dioxide is very important, because plants use it to make food, such as glucose. Plants take in carbon dioxide through their leaves and water through their roots. With the help of the green substance called chlorophyll, and using the energy of sunlight, plants turn carbon dioxide and water into glucose. We don't fully understand how this process works, but without it none of us would be alive. This beautiful and fantastic process is called **photosynthesis**, and it can be represented in this way: (4)

(4) Carbon dioxide is also a variable gas. Discuss the increase of carbon dioxide as caused by man and his engines. At the same time, consider the increased amounts of CO_2 as a factor likely to be expressed in a changing climate. See *Scientific American*, April 1952, "Volcanoes and World Climate," by Harry Wexler.

$$\text{energy from Sun} + 6CO_2 + 6H_2O \xrightarrow{\text{chlorophyll}} 6O_2 + C_6H_{12}O_6$$

carbon dioxide water oxygen glucose

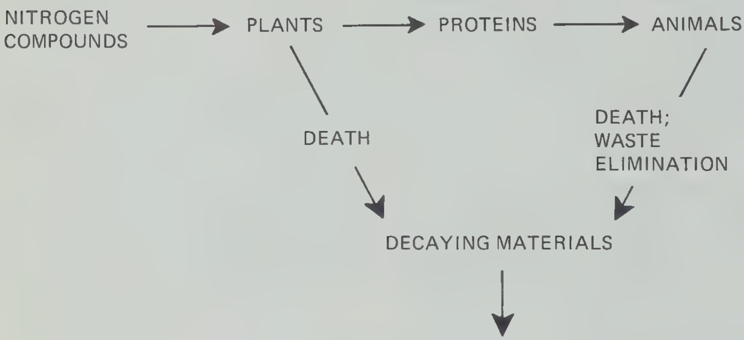
Nitrogen, too, plays an important part in all life processes. Nitrogen is an essential part of the proteins that make up the flesh and bones of your body. There is much nitrogen in the air around us (how much?), but we cannot use it directly. We must rely on plants to take in nitrogen to build the proteins.

Plants cannot take in nitrogen directly from the air either. They rely on various kinds of bacteria and algae that live on the roots of plants and change nitrogen from the air into nitrogen compounds, which they give to the plants. Plants also rely on other kinds of bacteria that live freely in the soil and make nitrogen compounds from decaying materials; these compounds are then taken in by plants through their roots.

activity 12.1 The nitrogen cycle

Try to draw a diagram to show what happens to nitrogen in nature. (This won't be easy!) For example, you know that nitrogen compounds are taken in by plants, which make proteins. The proteins are taken in by animals (including you) when they

eat the plants. Both plants and animals decay when they die. (The waste products of animals are also a rich source of decayed material.) So you can start your diagram this way:



Draw as much of the diagram as you can. Your finished diagram will not be complete, because you have not been given enough information to make it complete. But at least it should give you an idea of what scientists mean by the "nitrogen cycle." The nitrogen cycle is one of many, many cycles in nature. (1) (1) See Commentary, page T16

Because of exploding population and hunger in many parts of the world, man "helps" the nitrogen cycle along by adding nitrogen compounds to the soil to increase the growth of crops. Today, nitrogen-containing fertilizers that use nitrogen from the atmosphere are manufactured to help prevent starvation. But these fertilizers can be a source of pollution if not carefully controlled. Remember eutrophication? Man's "help" of nature is not always a help.

History of Earth's atmosphere. Have you ever wondered how our ocean of air got here and how it has changed through time? Do you think it is changing today?

Earth very early in its history lost most of its original atmosphere of hydrogen, helium, ammonia, and methane. This was due to the very high temperatures that existed at that time. Then, as the molten rocks cooled, they released gases that had been dissolved in the melt; carbon dioxide, water vapor, and nitrogen were the main gases released. (How does this composition differ from the present composition?) These gases are comparable to the gases that escape from volcanic

vents today. But interestingly enough, no life-supporting oxygen was present. When did the oxygen appear? Where did it come from?

Several theories have been given to explain the appearance of oxygen. Some scientists suggest that under the very high temperatures of an early atmosphere the water vapor (H_2O) would be broken up into oxygen and hydrogen. But oxygen and hydrogen can also recombine into water under these conditions. Others have reasoned that in a later time, when Earth was cooler, sunlight acting on water vapor in the upper atmosphere could break it up into oxygen and hydrogen. But there is surprisingly little water vapor in the upper atmosphere. The most widely accepted explanation says that the lower atmosphere got its oxygen when plants started to produce oxygen through photosynthesis.

In time the green plants started to use up the abundant carbon dioxide in a process of building plant tissue. (Plant tissue is made of substances that are made from glucose.) Normally the carbon dioxide would return to the atmosphere when the plant died and decayed. But some plants died in swamps and so they never completely decayed. Instead, they became fossil fuels, such as coal. The carbon dioxide that went into their formation never got back to the atmosphere. The immense coal fields found throughout the world give evidence of the great abundance of carbon dioxide in Earth's atmosphere in the past. Carbon dioxide was also removed from Earth's environment by countless numbers of small sea animals that used carbon dioxide in building their shells. The shells eventually turned into limestone. Thus carbon dioxide is tied up in the mountains of limestone rocks and the tremendous coal deposits over Earth's surface (Figure 12.3).

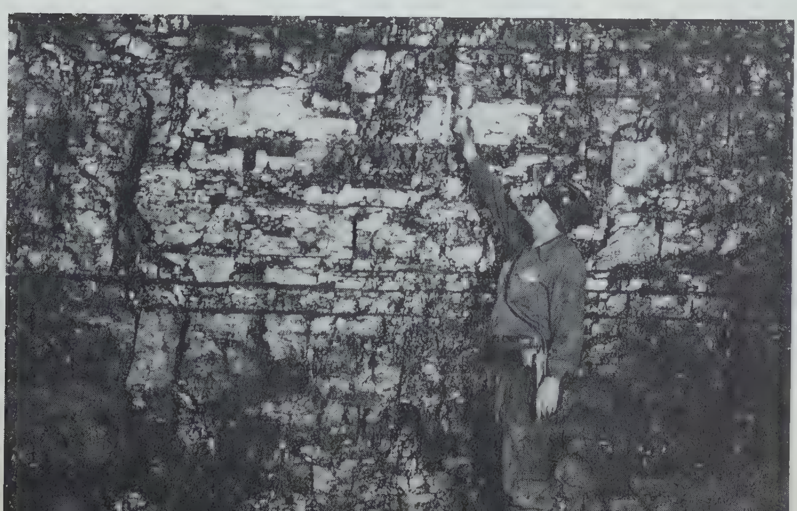


Figure 12.3 In this coal mine, "fossilized" sunshine and carbon dioxide have been stored for 350 million years.

Figure 12.4 Imagine what would happen to New York City if the sea level rose 60 meters.

With the removal of carbon dioxide from the atmosphere and the condensation of water vapor into liquid water, nitrogen became the most abundant gas and oxygen number two. Fortunately for us, the recipe turned out the way it did. This combination permits life to "tick" on planet Earth.

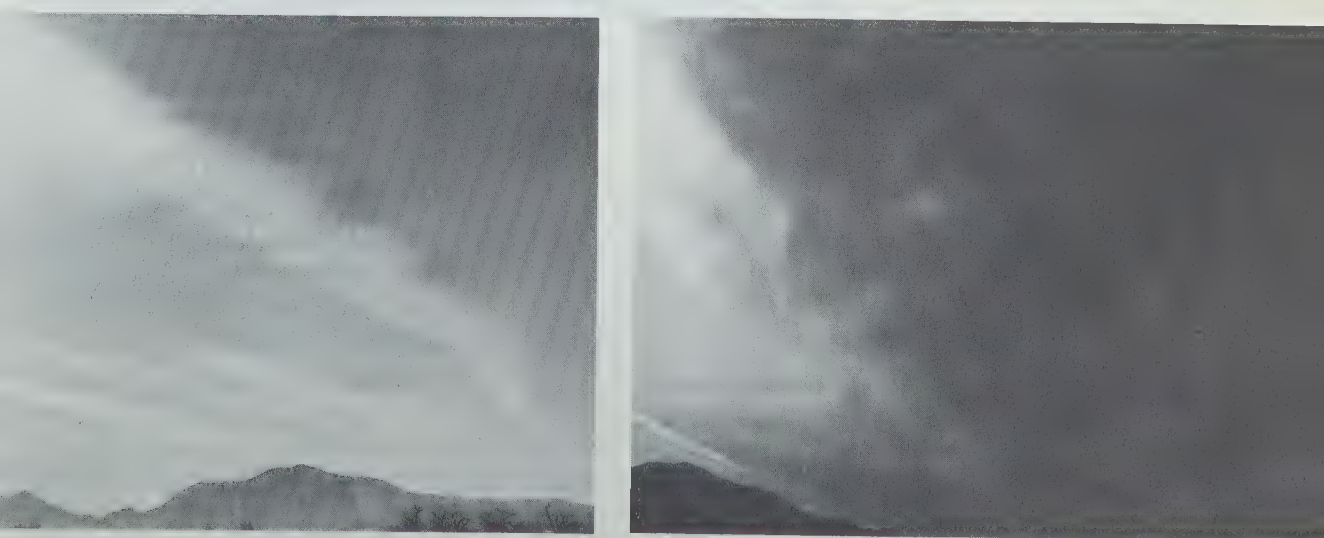
A changing atmosphere. The composition of the atmosphere over the surface of Earth and up to a height of about 80 kilometers has not changed greatly in a long time. That is a correct statement, but it fails to give us the entire picture. Some of the minor changes carry a tremendous impact. There are two gases in the atmosphere that vary in amount—water vapor and carbon dioxide. The amount of water vapor has always been variable. Over the humid tropics it will represent three to four percent of all gases present. Over the cold dry Arctic deserts the water vapor content is only a fraction of one percent.

The amount of carbon dioxide also varies, but in another sense. Since 1900 the total quantity of atmospheric carbon dioxide is estimated to have increased 10 to 15 percent. It is believed that this is caused by increased burning of fossil fuels such as coal, petroleum, and natural gas. More sig-

nificantly, it is believed by some atmospheric scientists that the warming trend in our climate is related to the presence of the carbon dioxide. The gas serves as an absorber of Earth heat. If the trend continues, the ice caps of Greenland and Antarctica could melt away. With their melting would come a rise in sea level of 30 to 60 meters. And when you consider how many of the large port cities of the world are located near sea level, we really have reason to be worried! (See Figure 12.4.) But don't sell your seashore cottage yet! All the facts are not in.

Strangely enough, since 1940 there has been a slight drop in temperature. This change could also be related to human activity. But it was not brought about by a well-planned operation by man to keep the ice caps from melting. Various pollutants that man has been putting into the atmosphere serve as a shield. A layer of solids and gases has been spread across the heavens like a thin curtain of cirrus clouds (Figure 12.5). They come and go as all clouds do, but their presence has added another variable to an already complex picture. This man-made curtain reflects a certain amount of Sun's energy back to space. The result: less energy coming in, less warming at the surface, and lower temperatures on Earth.

Figure 12.5 Jet aircraft contrails at left are spreading into thin cirrus clouds. In the photograph at right, taken two hours later, they are merging into a thin veil covering the whole sky.



Yes sir, with the explosion in our modern industrial way of life over the last few decades, there have been some noticeable additions to and changes in our ocean of air. Table 12.2 has been prepared to give you an opportunity to review some of the new ingredients that we all contribute every day.

Who is responsible for these ingredients? Most of us will point an accusing finger at industry and the big cities. But it is not that simple. All of us are polluters. Not only the city dweller; our country friends are also involved. Even your grandparents and generations beyond them polluted. Let's back off and take a look.

Do you think modern man has been the only one to use the atmosphere for disposing of waste materials? Is air pollution something new? What about primitive society? It was com-

Table 12.2 Air pollutants
(With all this, some people still smoke!)

Carbon monoxide (CO)	CO is produced when fuel is burned inefficiently. When fuel is burned efficiently, the combustion products are carbon dioxide (CO_2) and water and some other substances, but little CO. CO is very poisonous. When inhaled, it is absorbed into the bloodstream, where it interferes with the blood's transportation of oxygen to the tissues of the body.
Hydrocarbons: various compounds of carbon and hydrogen	Hydrocarbons are the main components of petroleum, gasoline, and other fuels. Some unburned hydrocarbons are released into the atmosphere by engines along with the exhaust (combustion products). In the presence of sunlight, the hydrocarbons combine with nitrogen oxides to form some components of a kind of smog called photochemical smog.
Nitrogen oxides: nitric oxide (NO) and nitrogen dioxide (NO_2)	NO is produced under high temperatures, such as those in the combustion chambers of engines. In a series of chemical reactions, NO combines with oxygen to form the poisonous gas NO_2 and the poisonous gas O_3 (ozone). NO, NO_2, and O_3 are some components of photochemical smog.
Sulfur oxides: sulfur dioxide (SO_2) and sulfur trioxide (SO_3)	SO_2 is produced in the burning of fuels containing sulfur, such as some kinds of coal. SO_2 combines with oxygen to form SO_3, which then combines with water vapor to form microscopic droplets of sulfuric acid (H_2SO_4), a highly corrosive substance. Sulfur oxides are very damaging to lungs.
Particulates: particles of solid and liquid substances	Particulates include particles of ash, oil, acids, asbestos, and other minerals, metals, metallic compounds, radioactive isotopes, and many other substances. Some particles are big enough to be visible. Some are microscopic in size and can stay suspended in the atmosphere for long periods of time. The liquid particles in the atmosphere are called aerosols.

Figure 12.6 Enormous amounts of matter are thrown into the atmosphere by volcanic eruptions.

mon practice for man to burn his wastes. Uncontrolled fires generated huge clouds of smoke and haze. The smoke drifted about in the restless air. Some of the material in the smoke would fall out, but other materials would stay in the air for a long time. Waste burning is still a common practice.

Take one more step back from the problem. Do you suppose there were any pollutants released before man came into existence? Yes sir! Long, long before "Smokey the Bear" posters appeared, lightning sparked many a forest fire—and it still does. Volcanic eruptions have ejected gases, fumes, and dust into the atmosphere with a force that only a volcano can muster (Figure 12.6). There have been winds sweeping across

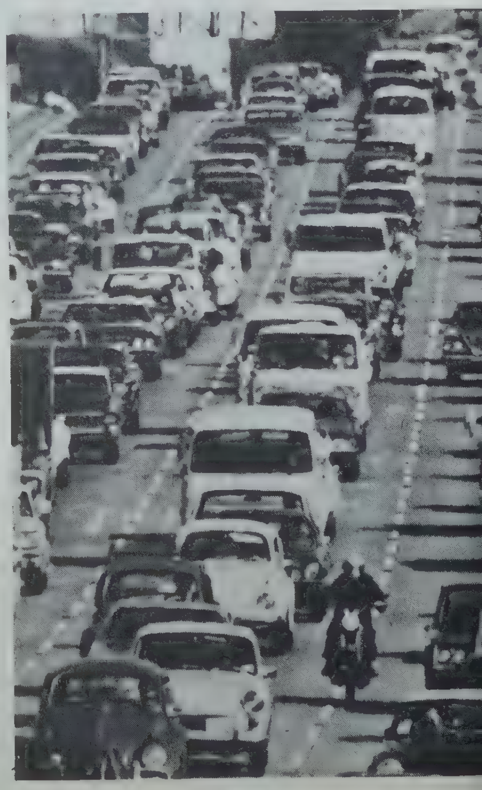
deserts as long as there have been deserts to sweep. Enormous amounts of dust have been removed from the drylands of all continents. This kind of pollution has been around for a long time.

If pollution is so common and if it has been around for such a long time, then why be concerned? In primitive society there were relatively few people to contribute to pollution, whereas now there are many more. But more significantly, our urban-industrial way of life is adding many *new* pollutants to the atmosphere (Figure 12.7). Think of all the automobiles, jet planes, and factories. Radioactive pollutants came in with the atomic age. All these pollutants are new, and we really have no idea what harmful effects many of them will produce in the long run. We are also putting more and more of these pollutants into the air at an ever-faster rate.

What's to be done about it? The attack on the problem must be along two fronts. First, there is the scientific-technical front. We can and must find new energy sources and better control of pollution-producing processes. To control it all is impossible, but we can improve greatly on the offenses of today. You may not be able to contribute to these efforts right away. Some of you may, however, through your training in science and engineering, contribute greatly along this front in the future. But you *are* in a position at this moment to attack along the second front—by expressing how you feel to public officials and industry representatives. We as citizens of Earth must refuse to accept excessive pollution. There will be a price to pay, but we must not give up so easily. Out of our efforts will come anti-pollution laws that will stop the activities of those who do not have any respect for the Earth they live on.

The *millibar* is a unit of pressure equal to 1000 dynes per square centimeter. Atmospheric pressure is also expressed in terms of the pressure exerted by a column of mercury. For example, standard atmospheric pressure is equal to the pressure exerted by a column of mercury 760 millimeters (about 29.92 inches) high. Thus, you often see standard atmospheric pressure written as 760 mmHg or 29.92 in. Hg. (Hg is the chemical symbol for mercury.)

Figure 12.7 Every vehicle is pouring pollutants into the atmosphere.



A LAYERED ATMOSPHERE

If you could cut a slice down through the atmosphere, you would be impressed with the variety of different layers. Some of these layers are thin and others thick, some warm and others cold, some heavy and others light. Some changes from layer to layer happen quickly, whereas other changes are gradual. The way we divide the atmosphere into layers depends on what property (characteristic) we are talking about.

Pressure and temperature changes. Suppose we start with the easy property: density. How does the density of air change from the bottom of the atmosphere to the top? The density of air would obviously be maximum at the bottom, because the air molecules there are pressed closer together by the weight of the air above them. A cubic centimeter of air at sea level would contain many more molecules than a cubic centimeter of air at 50 kilometers up. The pressure of the atmosphere at sea level is 100,000 newtons per square meter, or 14.7 pounds per square inch. (Remember? Look back at the discussion of the rock cycle in Chapter 2.) This pressure is called standard atmospheric pressure or one atmosphere. It is frequently expressed as 1013.2 millibars. (See the more detailed explanation of standard atmospheric pressure on page 254.) This pressure on our bodies is balanced by the internal pressure within our bodies; otherwise we would be crushed.

Pressure in the lower atmosphere drops off quite rapidly. At 5 kilometers, which is not a really high altitude, one half the atmosphere by weight is below you; the pressure there is one half the pressure at sea level. This fact may give you some appreciation of how compressed the surface air is. Many mountain peaks approach $5\frac{1}{2}$ kilometers, and several are two or more kilometers higher. At 18 kiometers, 90 percent of the atmosphere is below you. At 50 kilometers, 99.9 percent is below. From 50 kilometers out to 30,000 kilometers, the remaining one tenth of one percent is spread very, very thin. This gradual decrease of pressure presents a most graceful curve when plotted on a graph (Figure 12.8). (1)

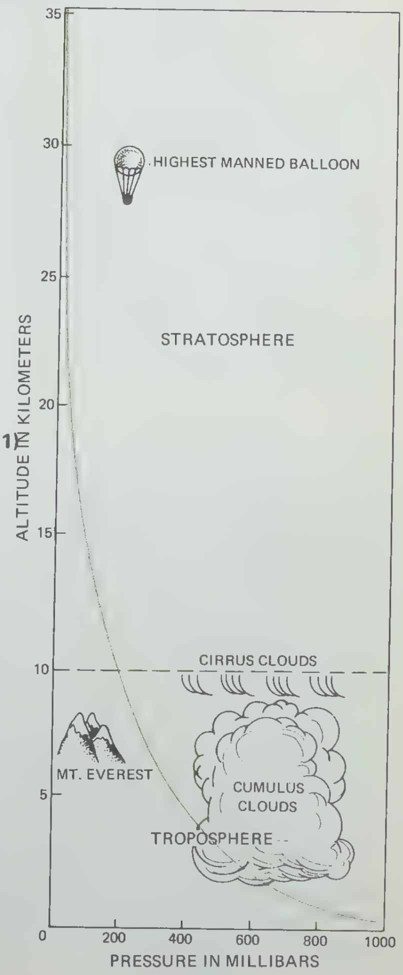
Now let's use temperature (rather than pressure) to define the divisions of the atmosphere. The zig-zag curve of temperature (Figure 12.9) is in striking contrast to the smooth pressure curve.

The temperature changes are related to an intricate relationship that exists between the atmosphere and solar energy. We seldom think of these two natural phenomena in the same context. Yet few things interact so intimately and with such important results. Without solar energy the ocean of air would be quite different.

Solar energy (such as light) travels earthward at about 300,000 kilometers per second. The trip takes 8.3 minutes. But it takes only a small fraction of a second to pass through the atmosphere. During this time, however, many interesting things happen. Some of these happenings are vital to every one of us, whether we know it or not.

(1) Although the changes in temperature aloft follow a zigzag pattern, it is important to note that the changes are predictable and not random. There are three zones of warming that keep the temperature curve to the right of the 0°C line (Figure 12.9): At Earth's surface, in the ozone layer, and in the ionosphere. It is important to have your students see and appreciate that temperature behavior aloft is not so capricious.

Figure 12.8 Pressure decreases rapidly with altitude.



Troposphere. In the lower part of the atmosphere, the decrease in temperature with height is about 6.5°C per kilometer. At approximately ten to 15 kilometers the temperature drops to a low −60°C. Why wouldn't it be warmer at 15 kilometers? After all, you're nearer the Sun there. True, but the Sun is not the direct heat source for the lower atmosphere. Have you thought about that? The lower layer of the atmosphere is warmed by the warmed Earth. The air nearest the warmed Earth is obviously the warmest. Since the air is warmed at the bottom, there is a tendency for it to overturn. The lighter warmed air is buoyed up and the cooler air sinks and replaces it. This characteristic restlessness gives the lower sphere the name **troposphere**—the sphere of overturning (*tropo* is Greek for "turn").

CHECK YOUR FACTS (1)

1. What are the two most common gases in the atmosphere?
2. What is one form of respiration?
3. What is photosynthesis?
4. Can we live without nitrogen?
5. How did the lower atmosphere get its oxygen?
6. What are some ways in which man has changed Earth's atmosphere?

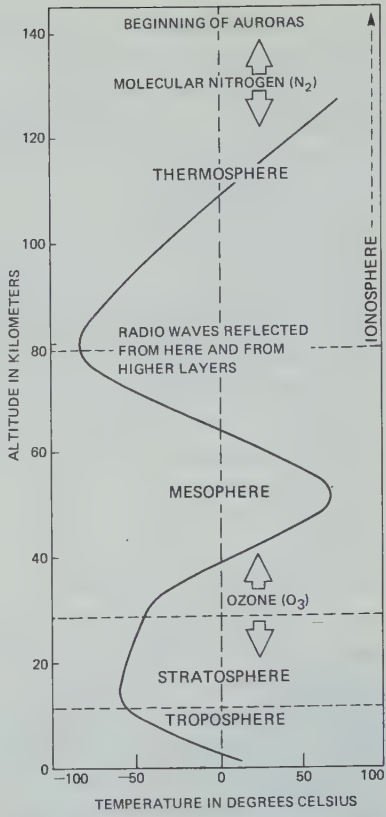


Figure 12.9 Temperature varies greatly with altitude.

(1) **ANSWERS** / Check Your Facts

1. Nitrogen (78%) and oxygen (21%).
2. Use of oxygen for vital functions.
3. Trapping of the Sun's energy by plants to form carbohydrates.
4. No. The nitrogen we breathe cannot help us because the nitrogen molecule (N_2) is so stable. Nonetheless, nitrogen is essential in the protein making up our bodies. We must rely on plants or animals that consume the plants for this essential nitrogen. "Nitrogen-fixing" bacteria in the soil can break up the stable nitrogen molecule, and the plants can pick up the nitrates through their roots. People are like shipwrecked sailors on a desert island dying of thirst because they cannot use sea water. We are surrounded by an immense ocean of nitrogen in the atmosphere, but we would soon perish if the plants failed to help us obtain it in a form we can use.

Stratosphere. Above the troposphere and up to 29 kilometers there is a gradual warming. Then a sharp increase takes place, until at 48 kilometers the temperature reaches a surprising 77°C. This is a stable layer, because the cold, heavy air is on the bottom. The stability means little vertical air movement and the air becomes stratified (layered)—thus the name **stratosphere**. But why should it be warm in the stratosphere? The reason is the absorption of solar energy in the ozone layer. Ozone! What is ozone? You are familiar with the gas oxygen, right? Well, ozone is a near relative to oxygen. Each ozone molecule contains three oxygen atoms. The ultraviolet rays from the Sun break up the oxygen. The free atom of oxygen will then collide with existing oxygen molecules and the result is ozone: O_3. The process can be written like this:

$$O_2 \xrightarrow{\text{ultraviolet rays}} 2\,O$$

diatomic oxygen 2 free oxygen atoms

$$O + O_2 \longrightarrow O_3$$

free oxygen diatomic oxygen ozone

Ozone is a poisonous gas; a minor trace can be found in the lower atmosphere. Some of it may be moved down from the stratosphere by air motion and some is formed by lightning flashes. Fortunately it does not accumulate in the troposphere. Ozone can be broken up by solar energy in the reverse process of its formation. The result is that the molecules of ozone are constantly being formed and destroyed (Figure 12.10). The most important function of this ozone layer is filtering out the intense ultraviolet rays. Without the absorbing capacity of this layer, the ultraviolet rays would fry us to a crisp. So with regard to ozone we are in a bind. We cannot live without its presence in the stratosphere as a shield, but we cannot live in its presence on Earth. Strange situations are found in nature!

Mesosphere. Beyond the stratosphere comes the **mesosphere**. Here the temperature decreases with altitude just as it did in the troposphere, and for the same reason. In the troposphere the Earth was the source of warmth, whereas in the mesosphere it is the ozone layer that provides the heat. The temperature throughout the mesosphere decreases until it reaches a low of −90°C at 80 kilometers. This is the lowest temperature reached in the atmosphere.

Thermosphere. The top of the mesosphere, at 80 to 89 kilometers, marks the most important change in the atmosphere. It is the beginning of the **thermosphere**. In the thermosphere temperature climbs to about 2000°C. A temperature of 2000°C seems extreme. But is 2000°C in the thermosphere the same as 2000°C at Earth's surface? No! At 400 kilometers the air is so thin that temperature as we know it is meaningless. As temperature increases at Earth's surface, the molecules and atoms making up the gases vibrate rapidly and the collisions among them are frequent. Heat energy is transferred in these collisions. In the thermosphere, however, there are so few atoms and molecules bouncing around that they would not pass on much warmth.

5. Most scientists believe that oxygen came with the development of primitive life forms. The very earliest forms were undoubtedly anaerobic bacteria, which can exist without oxygen in their environment. The initial oxygen came as a by-product from the metabolic processes of anaerobic bacteria.

6. By burning coal and oil, man has increased the carbon dioxide content of the atmosphere by 12% since 1880. It is estimated that our chimneys and exhaust pipes pour out 12 billion tons of carbon dioxide each year. There is a likelihood that the increase in atmospheric temperature since 1880 is related to the increase in carbon dioxide. Yet there are earth scientists who feel that the cooling trend since the 1940s may be a result of the increase in particulate matter in the air—tiny solid and liquid particles. This (2) man-made curtain of particles across the sky reflects a portion of the Sun's energy back to space. Sulfur compounds from industrial processes combine with water vapor to produce a weak acid. The action of sunlight on waste gases produces ozone. The sulfur dioxide and ozone are associated with human activity and they are irritating and corrosive.

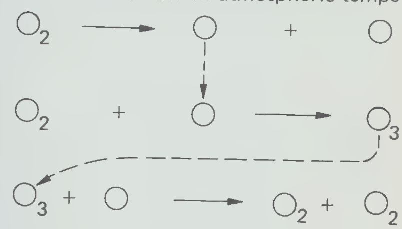


Figure 12.10 Formation and destruction of ozone.

(2) The students' awareness of the importance of the ozone layer and ionosphere in screening out the Sun's rays that would otherwise destroy life is more important than their observing temperature and pressure changes through the layered atmosphere and recording them in chart form. If you succeed, your students will develop an appreciation of such phenomena.

Up to the thermosphere the composition of the atmosphere is surprisingly uniform. Beyond it, however, the gases occur in layers, depending on their weights. We could call this "gravitational demixing." The lowest layer is molecular nitrogen (N_2), since it is the heaviest. Then comes atomic oxygen (O), next a helium layer, and finally the light gas hydrogen makes up the layer from 2500 kilometers out to 10,000 kilometers (look back at Figure 1.5). There is no well-defined upper boundary to the hydrogen layer. Beyond the 10,000 kilometers the number of hydrogen atoms would be about the same as in the broad expanses of space between planets. Yet even at 35,000 kilometers some of the hydrogen atoms seem to be following Earth's motions. They thus become part of the atmosphere of our planet. It is difficult to believe that our atmosphere reaches out so far.

Ionosphere. Cutting across the upper layers of the atmosphere is still another sphere, the **ionosphere**. It includes a part of the mesosphere and all of the thermosphere, but it is not a separate region such as the troposphere, stratosphere, mesosphere, or thermosphere. Yet it is there, and important to us and for several reasons.

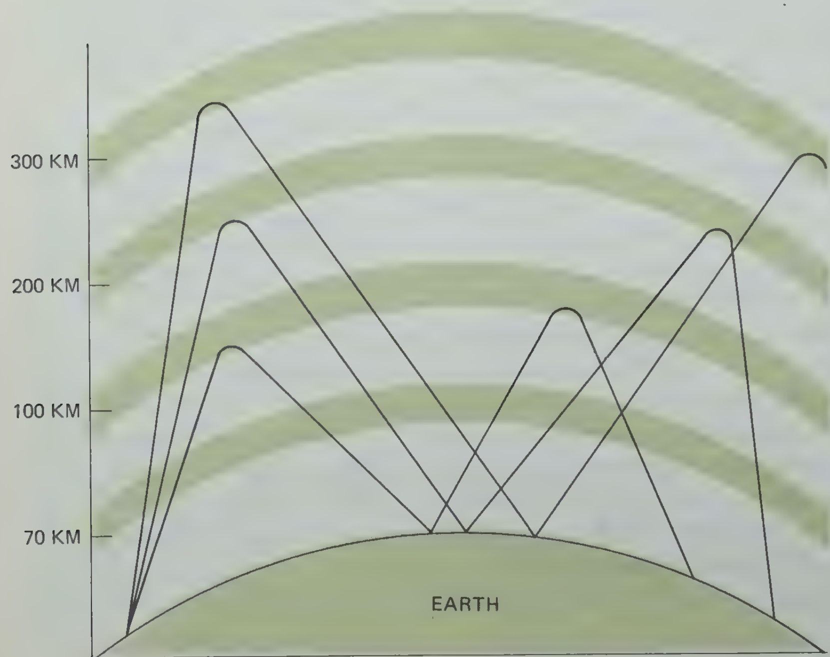


Figure 12.11 Radio waves are reflected from the ionosphere.

Figure 12.12 This brilliant aurora was photographed in Alaska.

From 80 to 400 kilometers there is an electrically charged layer. Perhaps we would say from 50 to 1000 kilometers, but the charge is greatest between 80 and 400 kilometers. As the energetic gamma rays and X rays from the Sun enter the layer of nitrogen and oxygen, they are absorbed. It is this action that is responsible for the high temperature of the thermosphere. In the process, electrons are given up by the molecules and atoms and they become positively charged ions. Therefore, this electrically charged area is known as the ionosphere. We should be thankful for the absorption, because X rays and gamma rays would kill us even more quickly than ultraviolet rays would.

The bottom of this ionized sphere reflects radio waves back to Earth (Figure 12.11). Without these ionospheric layers, there would be no radio reception from sources beyond 80 to 100 kilometers. Why? Because radio waves travel in a straight line and Earth's curvature would prevent any reception beyond this distance.

The most spectacular feature of the ionosphere is the (1) colorful aurora borealis, better known to us as the northern lights (Figure 12.12). (An aurora in the Southern Hemisphere is called aurora australis.) Auroras occur when atoms and molecules of hydrogen and oxygen in the ionosphere are excited by particles of the solar wind and give off a greenish and sometimes a red and violet glow. These colors sweep and roll through the sky. They may last only moments, or they may play for hours. The solar particles that produce the auroras tend to follow Earth's magnetic lines of force. Therefore auroras occur near the poles, where the lines of force dip down into the atmosphere (look back at Figure 1.4). Most of us living in the contiguous United States (the United States except Alaska and Hawaii) have few opportunities to experience these aerial displays. If you live in Alaska, however, or northern Scandinavia, you could count on such displays nearly every night—if there are no clouds. On occasions of violent solar outbursts, when Sun sends out unusually large numbers of particles, the particles move closer to Earth before following the magnetic lines of force. Under these conditions the citizens of Ohio, California, and points even farther south may see auroras.

CHECK YOUR FACTS (2)

1. What is the direct heat source for the lower atmosphere?
2. Is the stratosphere a stable or unstable layer?
3. What is ozone?
4. How high does the temperature get in the thermosphere?
5. What gas is found above 35,000 kilometers?
6. Where do auroras occur?

APPLYING WHAT YOU HAVE LEARNED (3)

1. What would happen if our air contained 21 percent carbon dioxide instead of 21 percent oxygen?

2. How would planting trees help to replenish the atmosphere's supply of oxygen?

3. Do you think that the percentage of water vapor in the atmosphere has not always been constant throughout geologic time? Explain.

(1) Few teachers or students have seen a good display of the aurora borealis. Take advantage of any personal experiences. Let some interested students explore the phenomenon in depth. Urge students to bring in colored pictures, if possible, because the patterns and colors of the aurora do change.

(2) ANSWERS / Check Your Facts

1. Earth radiation.
2. Stable, because the colder or dense, heavy air is at the bottom of the layer. The troposphere is unstable because the lower portion of the atmosphere is warmed by Earth's radiation. The warmer or less dense air is buoyed up. The weather we experience would be drastically different if this were not the case. Overturning would cease and the air would become stratified as it is in the stratosphere.
3. The ultraviolet rays of the Sun cause the atoms of oxygen in the molecules of O_2 to separate and then rejoin with another molecule as O_3. The absorption of the potentially harmful ultraviolet frequencies of solar radiation in the ozone layer warrants recognition because the ozone shield protects life on Earth's surface.
4. 2000°—perhaps.
5. A very rarefied hydrogen gas is found at 35,000 kilometers. This is about the same concentration as is found in space between planets. In the "gravitational demixing," hydrogen, the lightest gas, is found at 2,500 kilometers and extending to about 10,000 kilometers and beyond. There is no upper boundary to be identified. The interesting aspect of the hydrogen at 35,000 kilometers is the effect Earth's motion seems to have on it. If this effect actually exists we can say that Earth's atmosphere extends out to 35,000 kilometers.
6. Auroras are caused by particles ejected from the Sun into space. It requires about 30 hours for the particles and gases to reach Earth's atmosphere. Upon arrival they will excite the hydrogen and oxygen atoms and molecules of the Earth's ionosphere, and these in turn will glow with soft hues of green, red, and violet. The particles follow the magnetic lines around Earth and are therefore most concentrated and common in the polar areas.

(3) ANSWERS / Applying What You Have Learned

1. (a) Most animals would die. (b) The earth would get very hot because of the increased greenhouse effect.
2. Trees produce oxygen during photosynthesis.

4. In 75 years the atmosphere's carbon dioxide content has increased 15 percent. What do you predict for the next 75 years?

5. How would a thicker cloud formation or denser air mass affect the temperature of your environment?

6. Why does the atmosphere have different properties at different levels?

7. What is the relationship between ozone and oxygen? How could you make ozone?

8. If suddenly the ozone layer in the upper atmosphere disappeared, what might happen to life on Earth?

9. Why is temperature, as we know it, meaningless in the upper regions of the atmosphere?

10. What causes auroras?

11. What might happen to our environment if a layer of black dust from pollution was spread evenly over the polar ice fields?

12. Compare the density and temperature of the atmosphere at an elevation of 50 meters to that at 50 kilometers.

KEY WORDS

respiration (p. 246)
photosynthesis (p. 247)
troposphere (p. 256)
stratosphere (p. 256)
mesosphere (p. 257)
thermosphere (p. 257)
ionosphere (p. 258)

3. It most likely has not been constant. Since warm air can hold more water vapor than cold air, the atmosphere must have contained more water vapor during geologic periods when the temperature was higher.
4. It is difficult to make a prediction. The world will become more industrialized in the next 75 years; therefore, the increase may be more than the increase of the last 75 years. On the other hand, greater concern for the environment on the part of all nations may eventually produce a leveling off in the rate of production of carbon dioxide by mankind.
5. A thicker cloud formation would reflect more solar radiation back into space and produce a decrease in Earth's temperature.
6. The discussion in this chapter of the layers of the atmosphere serves as part of the answer. This is a very complicated question and no one has a full answer yet.
7. The relationship is shown in the diagram at the top of page 257.
8. The ultraviolet radiation striking Earth's surface would kill all higher forms of life.
9. The temperature of a gas is a measure of the average kinetic energy of the molecules of the gas. In the upper regions of the atmosphere, temperature is meaningless because there are so few molecules.
10. The auroras are caused by the excitation of air molecules by particles of the solar wind.
11. Earth would get warmer because (a) the polar ice field would not reflect as much radiation back into space (b) the black dust absorbs radiation. In warming up, the dust might cause partial melting of the ice fields and an increased sea level.
12. See page 255.

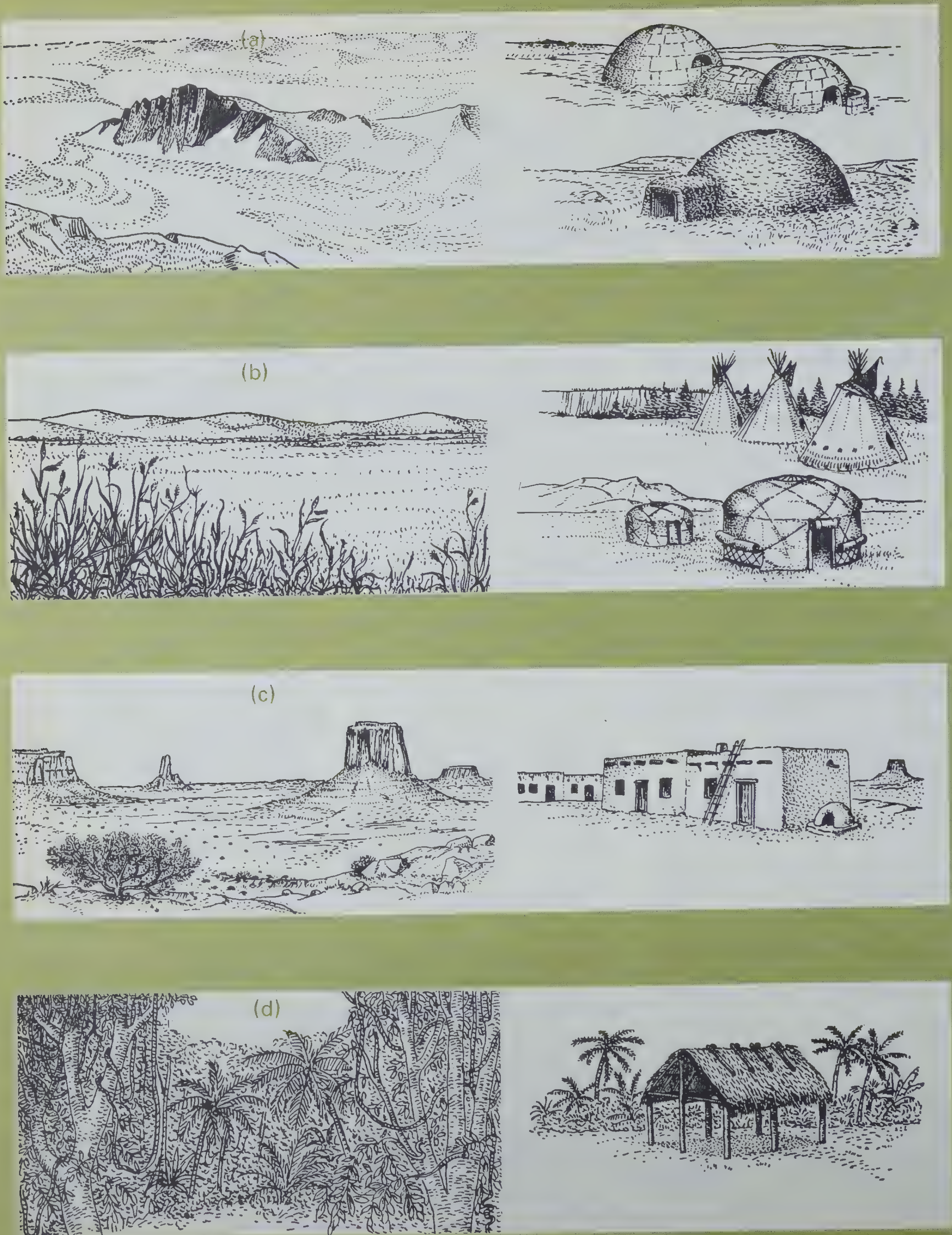

(a)
(b)
(c)
(d)

Figure 13.1 In this chapter you will learn why Earth has many different environments, such as (a), (b), (c), and (d) shown here.

Introductory Demonstration

See Commentary, page T16.

chapter 13

Weather and Climate

What subject do people talk about most? Probably the weather! Every news broadcast includes something about the weather. Weather is a favorite subject for starting conversations. And most of us don't realize how many expressions concerning the weather our language has. For example, if your lunch room or dining room is nicely decorated, you say it has *atmosphere.* A politician's speeches are sometimes described as just *hot air* coming from an old *wind bag.* The tendency of weather to change finds expression in the idiom *a fair weather friend.* And this lesson may be a *breeze* for some students but rather *foggy* for others.

What makes the weather? Although we have not directly mentioned the factors that go into the making of weather, the sentences in the last paragraph have identified them: temperature (is it hot or cold?), wind (is it windy or calm?), and pre-

cipitation (is it rainy or clear?). These factors work together in very complicated ways to make up the weather.

"But what about climate?" you ask. That is a term that we also hear when temperature, precipitation, and wind conditions in our area are discussed. Expressions like "This is sure a rainy climate!" or "I like the sunny climate here" are common expressions. Because of the similarity of these two terms, it is important that we distinguish between them before going on. **Weather** is commonly defined as the conditions of the atmosphere at a given time and place. **Climate**, on the other hand, is the weather conditions—including temperature, precipitation, and wind—that are characteristic of an area or region. So weather is what you experience at a particular time, and climate is the average of all the weather conditions taken over a long period of time. Keep in mind, however, that like everything else, weather and climate can and do change!

Now that we know the difference between weather and climate, let's take a look at the factors that go into their making.

WHAT KEEPS EARTH WARM?

The Sun is our most important source of heat. The planet Earth intercepts about one two-billionths of the total energy emitted by the Sun, and about one third of this amount is reflected or scattered back into space (Figure 13.2). The remaining two (1) thirds is absorbed by the atmosphere; it is what keeps us warm.

How does this two thirds get into the atmosphere? The processes are both simple and complicated. One of the easiest to understand is conduction, which you read about in Chapter 11. Conduction is the direct transfer of heat from molecule to molecule—from one substance to another. But since air is a poor conductor, the process is slow and of limited importance.

The greenhouse effect. Radiation, however, is of prime importance. In contrast with conduction, radiation is a process that does not require a medium of transfer. Solar energy travels through space as electromagnetic waves. (You will read about electromagnetic waves in Chapter 18.) Those waves that make up visible light (and some other electromagnetic waves as well) can penetrate the atmosphere; therefore most such waves reach Earth's surface. At Earth's sur- (2)

(1) Figure 13.2 shows what happens to the incoming solar radiation; it does not show the overall "heat budget" of Earth. In the overall picture, as much energy is lost by Earth as is gained by it. If this were not so, Earth could not maintain a steady temperature. If it retained more energy than it lost, it would get steadily hotter. Loss of energy by radiation into space is, of course, greater at night than during the day. It also varies with latitude. At the equator, more energy is gained than lost. At the poles, more energy is lost than gained.

(2) There are two "windows" for electromagnetic radiation coming through the atmosphere. One is the "visible window," which allows visible light to come through. The other is the "radio window," which allows radio waves (and other electromagnetic waves nearby in the spectrum, such as microwaves and radar waves) to come through. The atmosphere is opaque to other regions of the electromagnetic spectrum.

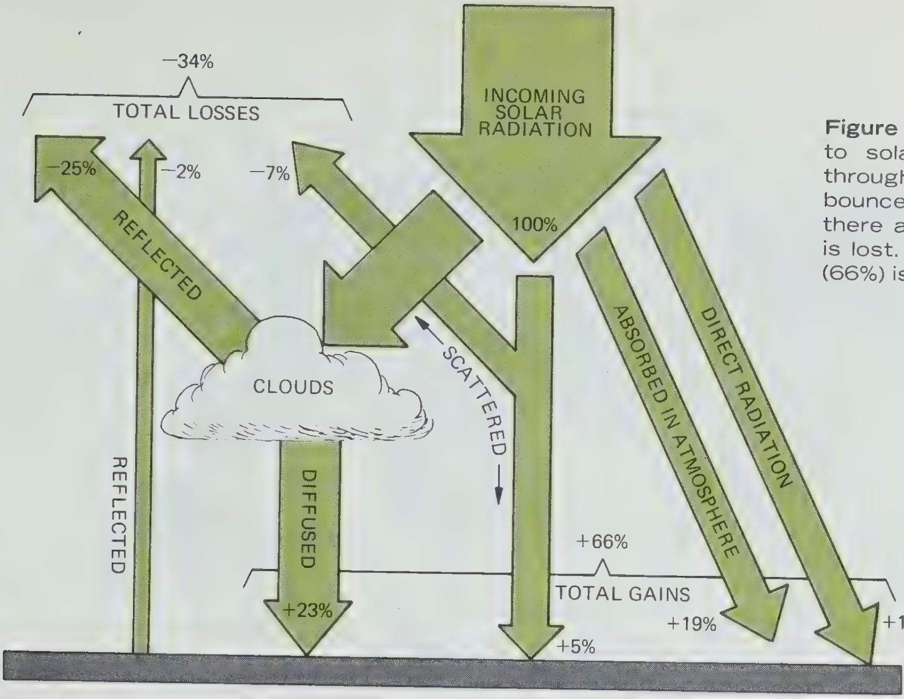


Figure 13.2 Many things happen to solar energy as it passes through our atmosphere. It bounces around from here to there and about one third (34%) is lost. The remaining two thirds (66%) is what keeps us warm.

face, however, a transformation of energy takes place. The energy is absorbed, and then it is re-emitted—but as waves of longer wavelength. These longer electromagnetic waves *cannot* penetrate the atmosphere easily. Therefore, instead of passing through the atmosphere and out into space, they are "trapped"—that is, they are absorbed by the atmosphere. This trapping of energy is called the **greenhouse effect** because it is similar to what goes on in a greenhouse. In a greenhouse, visible light passes through the glass or plastic windows and is absorbed and then re-emitted as longer waves. The longer waves cannot pass through glass or plastic easily, and so are trapped inside the greenhouse. (In the atmosphere, carbon dioxide and water vapor serve as the glass or plastic windows of a greenhouse. They absorb the longer waves, preventing them from escaping into space.) (3)

(3) **ANSWERS** / Check Your Facts

1. Weather is the condition of the atmosphere at a given time and place; climate refers to the weather conditions that are characteristic of a region.
2. Temperature, precipitation, and wind.
3. The Sun.
4. Earth radiation and conduction.

CHECK YOUR FACTS

1. What is the difference between weather and climate?
2. What are the three major factors that make up weather?
3. What is our most important source of heat?
4. How is the atmosphere warmed?

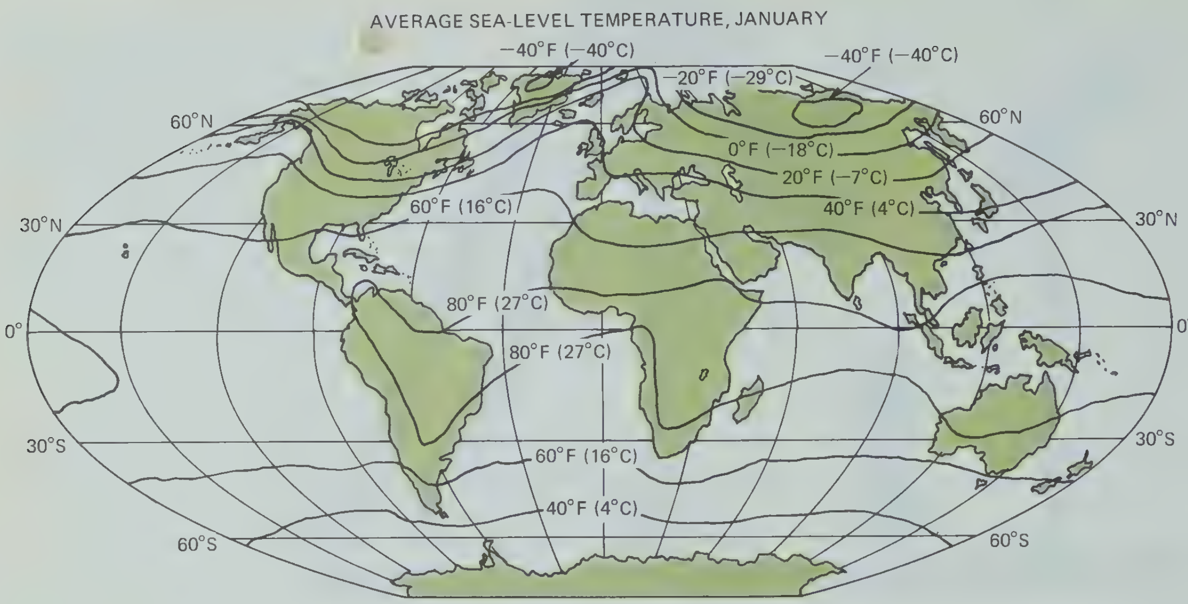


Figure 13.3 Compare the temperature distribution over Earth's surface in January (above left) and July (above right). Notice how the pattern changes.

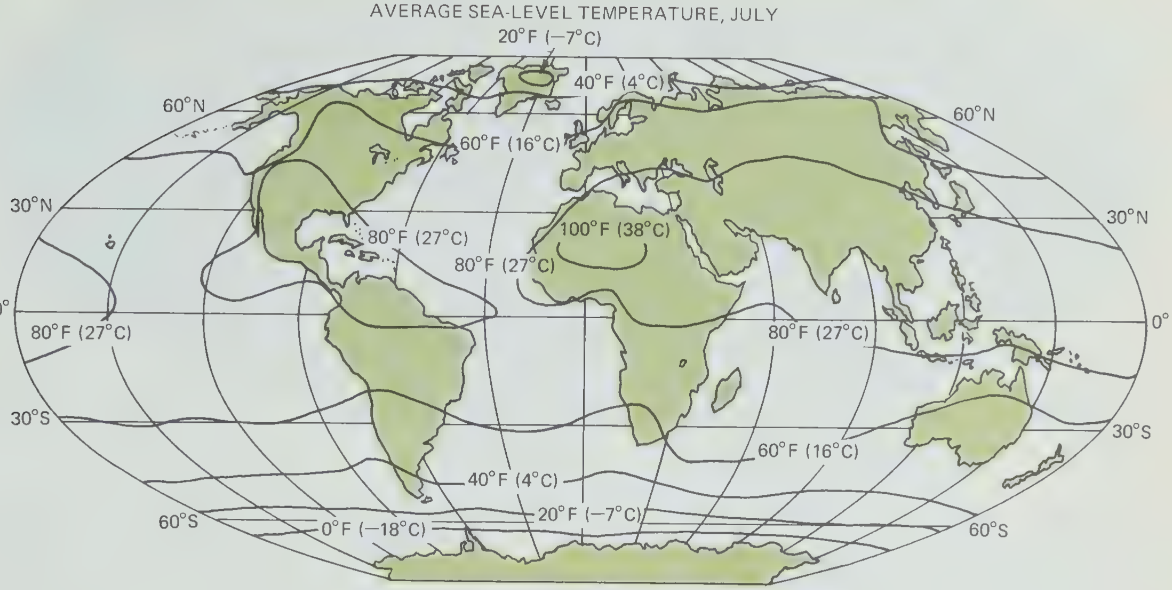
TEMPERATURE DISTRIBUTION

What can you say about temperature in various areas of the world? How does Alaska compare with Florida?

Take a look at Figure 13.3, which shows Earth's temperature patterns for January and July. The lines that extend across the maps are called **isotherms**; they connect points that have the same average daily temperature in the months indicated. If you read the temperature values of the isotherms you will note that the maximum temperatures occur in the tropical (low-latitude) areas, and the minimum temperatures occur in the polar (high-latitude) areas. This certainly should not surprise you. You have known for a long time that temperature decreases from the equator to the Poles. But why?

The unequal distribution of temperature over Earth's surface is caused largely by the spherical shape of Earth. Have you thought of this? If Earth were a cube, the temperature distribution would be quite different! Since Earth's surface is curved (Figure 13.4), the Sun's rays strike the tropical areas perpendicularly, or nearly perpendicularly. As you travel north or south of the equator, you find the Sun's rays striking the ground at more and more of an angle. Finally, at the Poles, **(1)** the rays are horizontal or nearly horizontal. Thus solar energy

(1) The situation shown in Figure 13.5 can be demonstrated with a flashlight if the classroom is not too bright. Shine the flashlight perpendicularly on a surface and have a student draw the area covered by the light beam. Then shine the light obliquely and again draw the area covered. The second area will be much larger.



falling on polar areas has to cover more ground than the same amount of energy falling on tropical areas (Figure 13.5). Also, energy falling on polar areas has to travel a greater distance

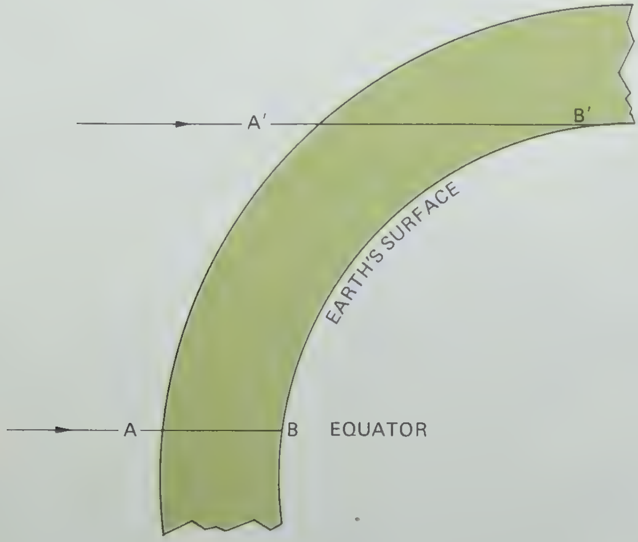


Figure 13.4 Ray A′B′ has to travel through more atmosphere (indicated by color) than ray AB.

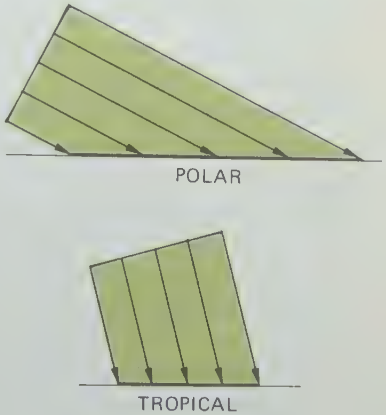


Figure 13.5 The same amount of solar energy (represented by beam of the same width) has to cover more area in polar regions than in the tropics.

through the atmosphere, as can be seen in Figure 13.4. Therefore, less of it gets through to the ground.

Now take another look at the maps in Figure 13.3. Do all the isotherms extend east and west? What about the isotherms (1) across North America and Eurasia? Don't they deviate noticeably from the general east–west pattern? Look at the isotherms in the Southern Hemisphere. They follow the east–west pattern almost perfectly. Why? Notice that the continents dominate Earth's surface in the Northern Hemisphere. It seems then that the explanation of the abnormal behavior of isotherms north of the equator is related to the presence of large continents. And in the Southern Hemisphere, the seasonal stability of the thermal pattern is related to the enormous bodies of water. But why?

(1) Yes.

As you learned in Chapter 11, the oceans are Earth's thermostat. Water is transparent and the rays of the Sun can penetrate it to some extent. This means that a large mass will be warmed slightly. The ground is opaque and warming is limited to a thin layer that heats rapidly. The waters move; there is much mixing in the oceans. The land does not move— (2) except, of course, slowly, over geologic time. Water has a much higher *specific heat* than land. This means that much more heat energy is needed to raise the temperature of a given mass of water by a given amount than is needed to raise the temperature of the same mass of land by the same amount. Complicated? It may help you to think of it this way: Water absorbs more heat than land; it is a good storer of heat. Because it is a good storer of heat, it is also a good distributor of heat. It absorbs a lot of heat from warm regions of the world and, when it flows to colder regions, gives up a lot of heat. Without the oceans, hot regions would be even hotter and cold regions would be even colder.

(2) It takes 1 calorie of heat to raise 1 gram of pure water by 1°C. It takes only 0.12 calorie to heat 1 gram of iron by 1°C. The specific heat of water is 1; the specific heat of iron is 0.12. Most common substances have lower specific heats than that of water. You might ask the students which object would stay warmer longer: a hot-water bottle or an equal mass of iron at the same initial temperature. Since water has a higher specific heat (it "holds more heat"), the hot-water bottle would stay warm longer. It continues to release heat for a long time. The iron would quickly give up the heat it contains and drop to the temperature of its surroundings. Thus one takes a hot-water bottle and not a warm piece of iron to bed. A warm rock, on the other hand, would be better than iron because its specific heat is relatively high.

With these considerations in mind, look again at the January map in Figure 13.3. (In January, it is winter in the Northern Hemisphere and summer in the Southern Hemisphere.) Note how the isotherms in the Northern Hemisphere dip strongly equatorward around the cold continents. But note also how they reach poleward around the warm oceans. Because of this poleward and equatorward bending from ocean to land, the general east–west pattern is stretched in a north–south manner in some areas. The contrast in summer between continent and ocean is not as well defined as in winter. There is, however, a gentle curving of the isotherms poleward around the warm continents in the Northern Hemisphere. In the Southern Hemisphere the isotherms maintain the east–west

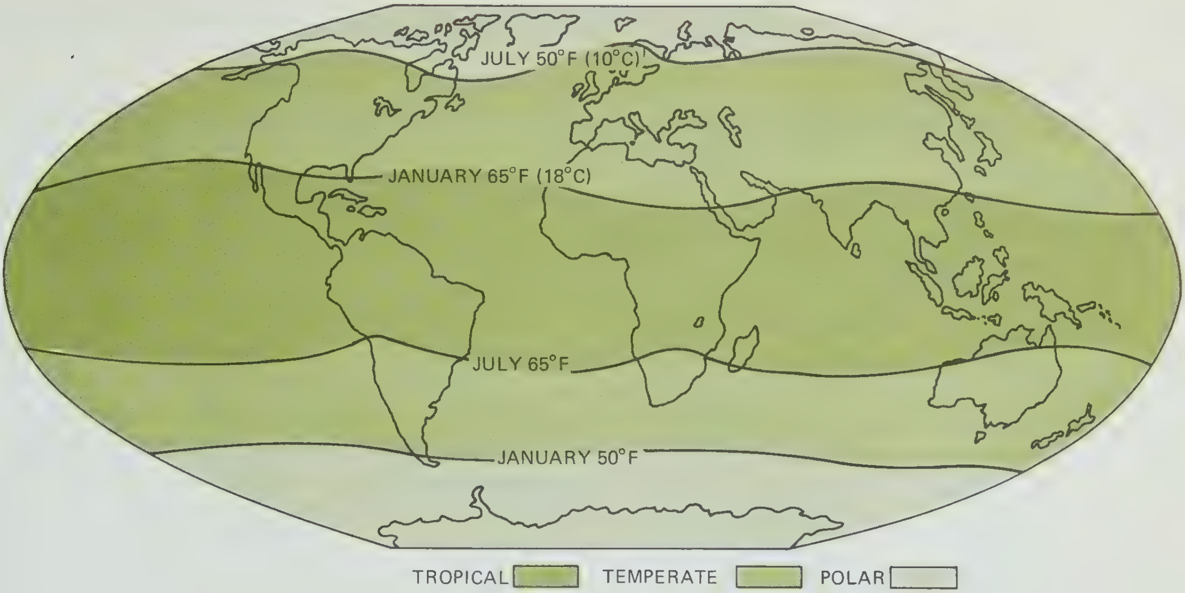


Figure 13.6 Earth's great thermal environments or zones are plotted on this map. Figures 13.4 and 13.5 show why there are such different zones. Of the environments shown in Figure 13.1, **(a)** is found in the north polar zone, **(b)** and **(c)** are found largely in the temperate zones, and **(d)** is found in the tropical zone.

orientation. There are no large continents there to interrupt the seasonal pattern.

Thermal zones. Now let's take the two maps and simplify them. Let's eliminate all isotherms except the two for the coolest month (18°C or 65°F) and the two for the warmest month (10°C or 50°F). (See Figure 13.6.) Why these values?

A temperature of 18°C for the coolest month is critical because it defines the limits of the **tropical zone**. When the average temperature of the coolest month is below 18°C, tropical plants begin to disappear from the landscape. It does not matter how hot it gets in the tropics; the critical issue for tropical plants is how low the temperature drops. A temperature of 10°C for the warmest month defines the limits of the **polar zones**. If the average temperature of the warmest month does not reach 10°C, trees run into problems. It does not matter how low the temperature may drop; the critical value for the growth and reproduction of trees is 10°C or more. When the temperature averages less than that, the forest disappears. The areas between the tropics and the polar zones are the middle latitudes or **temperate zones**. The northern temperate zone is where most of us live. Since they are betwixt and between, the temperate zones take on the characteristics of their neighbors. They can be as hot as the tropics and as cold as the Arctic.

CHECK YOUR FACTS

1. Why is temperature distributed unequally over Earth?
2. Why are the temperatures of 10°C and 18°C critical?

(3) ANSWERS / Check Your Facts

(3)

1. Because of the "spherical" shape of Earth.
2. They define the limits of the polar and tropical zones, respectively.

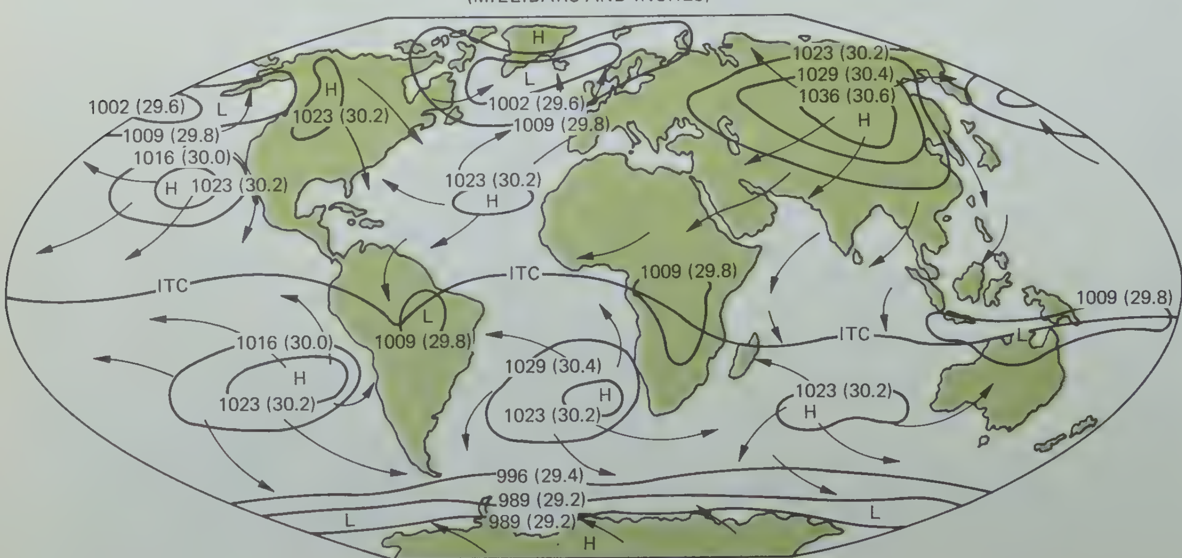
WIND AND PRESSURE

Temperature differences on Earth are more important than you may think. Temperature differences are related to pressure differences, and pressure differences are responsible for the winds. Let's consider one tiny example. On a winter day, the pressure of the cold, dense air outside your window is likely to be slightly higher than the pressure of the warmer, less dense air in your room. Open the window, and you will feel the cold outside air rush inside. Why? Because air flows from regions of higher pressure to regions of lower pressure. Winds all over Earth's surface work pretty much the same way as the "mini-wind" you created by opening the window.

The global patterns of wind and pressure in winter and summer are plotted on the world maps in Figures 13.7. At first glance the maps are bewildering—a big tangle of lines and arrows. But don't give up. There's rhyme and reason in the pictures. The lines are **isobars**; they connect points of equal pressure. As you can see, pressures over the world vary quite a bit from the pressure that is taken as standard atmospheric pressure: 1013.2 millibars (see pages 254 and 255). The arrows on the maps represent the winds. The letters **H** and **L** on the maps represent high-pressure areas and low-pressure areas (commonly called just "highs" and "lows," as you

Figure 13.7 The pattern of Earth's surface winds and pressure are shown on these maps. Winds are represented by the arrows and pressure is shown by isobars. (Standard atmospheric pressure is 1013.2 millibars or 29.92 inches.) Note how the pattern changes between January and July.

SURFACE WINDS AND PRESSURE, JANUARY (MILLIBARS AND INCHES)



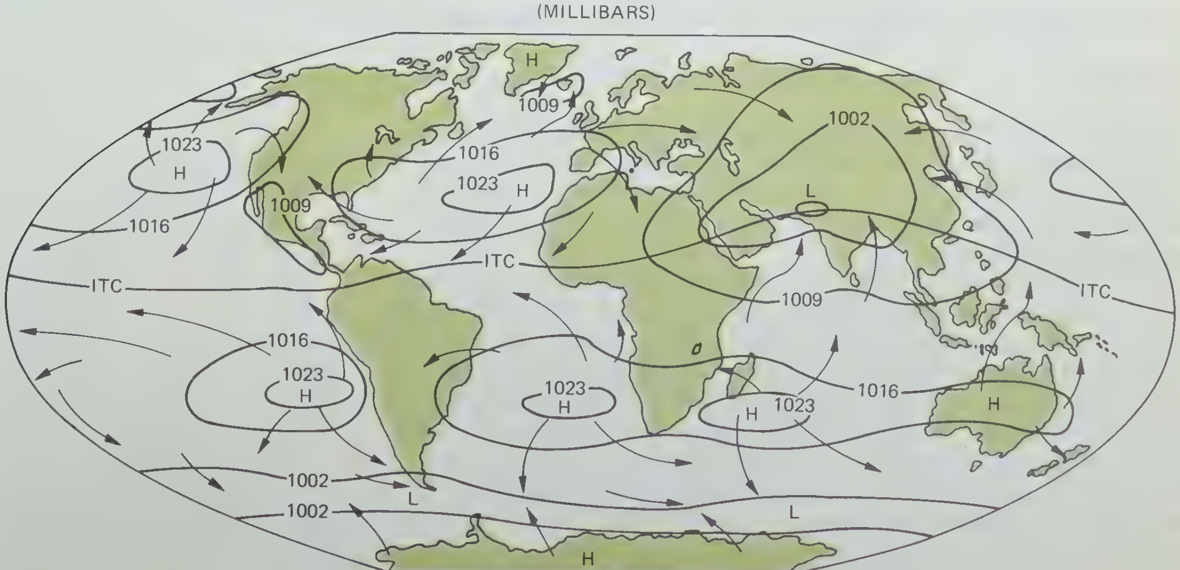
have undoubtedly heard on television). Why this pattern? What controls it?

The doldrums—a low. Let's start our investigation of pressure and wind with the low pressure area and adjacent winds near the equator. The area is called the **intertropical convergence zone** (ITC). It is also known as the **equatorial low** or the **doldrums**. The zone zigs and zags around the equator. And there is a seasonal shifting. You have to contrast the position of the ITC in January with its position in July to appreciate this feature. Do this! Let your eye follow the ITC on the January map across to the July map and back again. And note that the winds from the north and south tend to converge (come together) at the ITC. (These winds, called the **trade**(1) **winds**, are shown in the much simplified diagram of the global wind and pressure pattern in Figure 13.8. Note that winds are named for the direction *from* which they blow.)

(1) The trade winds received their name because they were used to good advantage by trading ships under sail.

Now the explanation of several features we have observed. Why a low pressure near the equator? Why the seasonal shifting? Why the trade winds and why are they not the same in both hemispheres? As you learned earlier in this chapter, the highest temperatures are found in the tropical zone. The surface air there absorbs a great deal of heat. As the air is warmed, it expands, becomes less dense, and rises. So here is the ex-

SURFACE WINDS AND PRESSURE, JULY
(MILLIBARS)



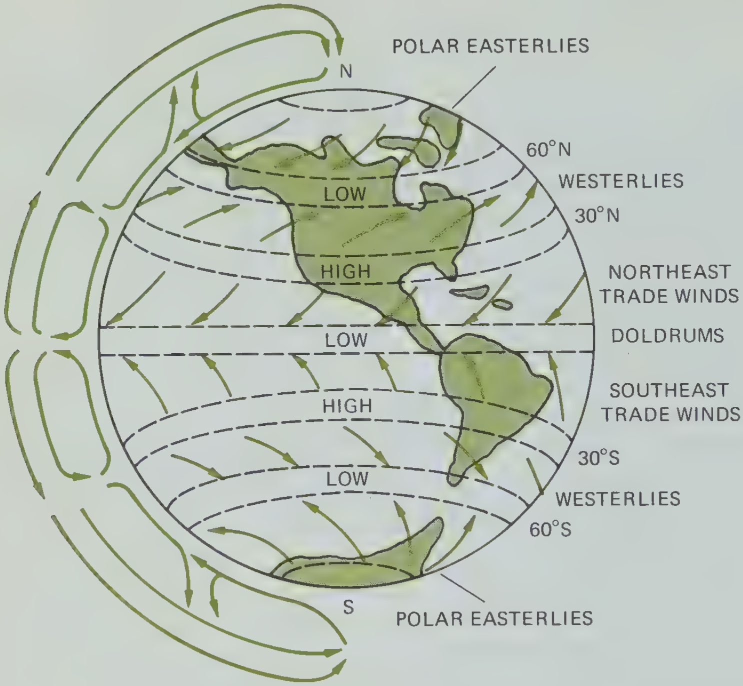


Figure 13.8 This is a very simplified diagram of the pressure belts and wind circulation patterns of Earth. The many irregularities in the pattern are not shown.

planation of why the equator is a region of low pressure: because the air there is leaving it! The air rises to the upper regions of the troposphere, where it splits, part of it moving north and part of it moving south, as shown in the left part of Figure 13.8. This is convection on a gigantic, global scale.

activity 13.1 Convection in a meatloaf pan

For this activity you will need a transparent, heatproof meatloaf pan (such as a Pyrex meatloaf pan), a medicine dropper, some colored liquid (such as ink or food coloring), a Bunsen burner, and a laboratory stand or tripod on which to put the pan while you're heating it.

Fill the pan almost full with water. Put it on the stand and put the lighted Bunsen burner under one end of it. Fill the dropper with the colored liquid. After a few minutes, insert the tip of the dropper into the water at the end away from the Bunsen burner, squeeze some of the liquid into the water, and withdraw the dropper. Watch the pattern made by the colored liquid. (If nothing happens, wait. A pattern will develop after the water gets hotter.) How do you explain the pattern? Which end of the pan represents the equatorial region? (1)

(1) Water rises at the heated end (therefore, that end represents the equator) and sinks at the cooler end. The colored liquid will show this circulation pattern.

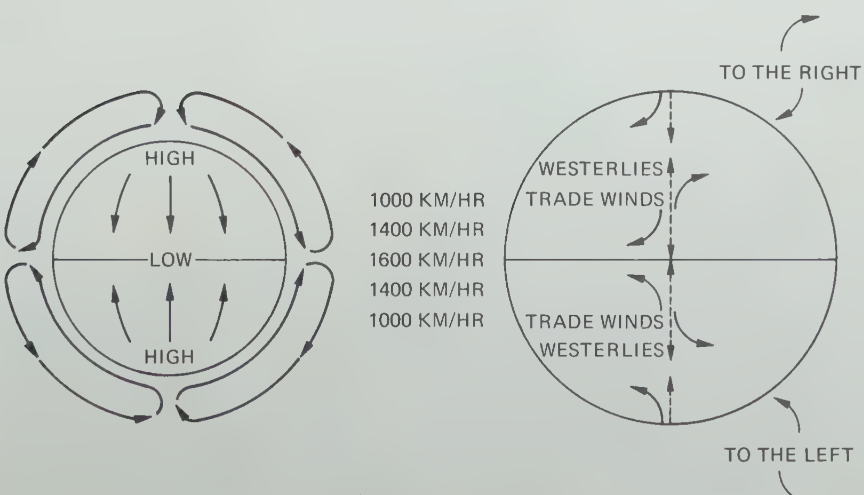
The seasonal shifting of the ITC is obviously tied up with the seasonal shifting of the temperature pattern. As the tropical region of high temperature shifts north and south from season to season, the equatorial low and the trade winds follow. They have no choice. They are Sun-controlled.

Do you notice something peculiar about the direction the winds blow? Look again at the left part of Figure 13.8. Air rises from the equator and sinks around 30 degrees north and south. From there, why doesn't it go straight back (directly south and directly north) to the equator? Let's carry this thought one step further. Since Earth is warmest at the equator and coldest at the Poles, why isn't the global circulation pattern the simple pattern shown at left in Figure 13.9? Air would rise at the equator, sink at the Poles, and from there move directly back to the equator. We would have only two kinds of winds—directly from the north and directly from the south!

But this is not so. For example, the trade winds in the Northern Hemisphere blow not directly to the south but to the southwest. They veer to the right from a southbound path. And the trade winds in the Southern Hemisphere veer to the left from a northbound path. Why?

The answer is our old friend from Chapter 11, the Coriolis effect. Since air is not firmly attached to Earth, a parcel of moving air (that is, a wind) tends to travel in a straight line, maintaining its original speed and direction. However, as the trade winds move toward the equator, they are moving from an area where Earth's surface rotation is about 1300 kilom-

Figure 13.9 If the Coriolis effect did not exist, the simple circulation pattern shown at left below would take place. The Coriolis effect causes winds to veer in the manner shown by the solid arrows shown at right below.



eters per hour to an area where the surface rotation is about 1600 kilometers per hour (Figure 13.9). Therefore the trade winds keep "falling behind" Earth's surface. To us, attached to the surface, this "falling behind" appears as a veering to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. And of course the Coriolis effect occurs with all winds, not just the trade winds. In fact, it can be observed in just about every kind of motion: ocean currents, the path of a missile—even the path of a rock you throw, if you had super-accurate instruments to measure it with.

Subtropical high—the gear wheel of weather. Poleward from the ITC is the most noticeable surface pressure pattern of the entire show. In Figure 13.7, note the highs at about latitudes 30°N and 30°S over the oceans. These are the **subtropical highs**. They form a dominating, east–west pattern. The winds swing about these high-pressure centers like immense gear wheels. In the Northern Hemisphere the motion is away from the high and clockwise around it. In the Southern Hemisphere the motion is away from the high and counterclockwise around it. On the equator side of these belts of subtropical highs, the winds are known as the stable trade winds; on the poleward side they are the stormy **westerlies**. Once you understand this basic, simple pattern of the subtropical highs and associated winds, you are on your way to understanding weather.

Now the big question. Why should there be such persistent features as the subtropical high? We don't know the complete answer, but we know part of it. As you learned earlier, air rises from the equator to the upper part of the troposphere, where it levels off and turns poleward. These winds are called antitrades. Because of the Coriolis effect, the poleward-moving antitrades veer more and more to the northeast in the Northern Hemisphere and to the southeast in the Southern Hemisphere. Finally, at about latitudes 30°N and S, these high-level winds begin to pile up and descend. This piling up and descending contributes to the high pressure at Earth's surface at these latitudes.

Another reason for the persistence of the subtropical highs involves cooling of the air rising from the equator. (1) Warm air can hold more water vapor than cool air. The warm air at the equator contains a great deal of moisture. As it rises and cools, it can hold less water vapor, and so water condenses out of it and falls as rain. (This is why it rains so much in equatorial regions.) When water vapor condenses to form

(1) It takes 540 calories of heat to turn 1 gram of liquid water into water vapor. When 1 gram of water vapor condenses into one gram of liquid water, this "latent heat" of 540 calories is released. Thus, when water evaporates from the sea, the sea is *cooled*. When water vapor condenses from the air into liquid water (rain), the air is warmed. This is one of the ways in which heat is transferred from the sea to the atmosphere.

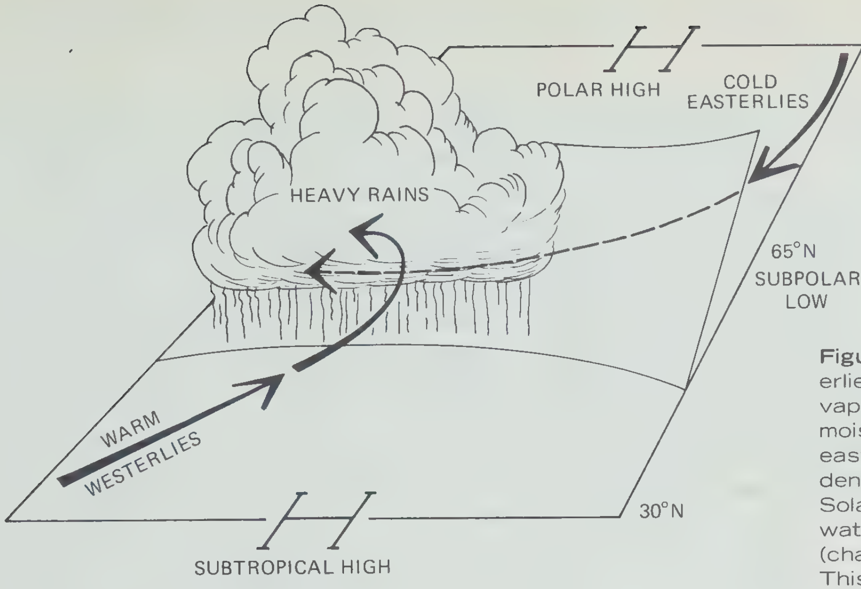


Figure 13.10 The warm westerlies pick up moisture (water vapor) from the ocean. As the moist air rises over the cold easterlies, the moisture condenses out as clouds and rain. Solar energy is absorbed by water when water evaporates (changes from liquid to vapor). This energy is "stored" in the vapor. When the vapor condenses to liquid, the stored energy is released in the form of heat. This released solar energy is what keeps the storm going.

liquid water, heat is released, *adding* heat to the air. However, when the air levels off at high altitudes to become the antitrades, it loses heat by radiation into space. The dry, cooled, denser air then sinks at the 30° latitudes, increasing the surface pressure there (producing a high). From there the air again splits—part of it flowing to the equator, joining the trade winds for another round, and the rest of it flowing poleward to become the westerlies.

Subpolar low—battleground of air masses. Going farther poleward, we find at about 65°N and S two other low-pressure zones. In the Northern Hemisphere there are two well-defined low-pressure centers in January: one in the North Atlantic near Iceland and the other in the North Pacific near the Aleutian Islands. In the Southern Hemisphere the low-pressure zone circles the entire Earth (Figure 13.7).

We can explain more easily why the subpolar lows happen to be where they are if we include in the discussion the polar highs. They are the last of the major pressure zones. At the Poles temperatures are low, and therefore the air is dense and the surface pressure is high. Out of these polar highs pour the cold, dry **polar easterlies**. They meet the warm, moist westerlies at about 65°. When these two very different air masses collide in the vicinity of the subpolar low, the battle of air masses takes place. The cold air hugs the ground and pushes equatorward. The warm air rides up over the invader (Figure 13.10). A counterclockwise flow of air builds up as the storm deepens, resulting in a middle-latitude cyclone, which will be discussed later in this chapter (Figure 13.12). A great deal of

rain condenses out of the warm air. The release of heat during condensation is responsible for the low pressure at these latitudes.

We have talked only about the worldwide patterns of winds and pressures—patterns that change only from season to season. But of course there are many other kinds of circulation patterns—ones that cover smaller areas and change more frequently, even between day and night. For example, in many coastal areas there is a breeze blowing from sea to land during the day (especially during a hot day), and a breeze from land to sea at night. What causes these breezes? (Hint: During the day, the land is warmed by the Sun. What happens to the air over the land?)

CHECK YOUR FACTS

1. How is wind related to pressure differences?
2. Why does air rise at the equator?
3. Why does it rain so much in equatorial regions?
4. What are some differences between the polar easterlies and the westerlies?

(1)(1) **ANSWERS** / Check Your Facts

1. Wind moves from a high-pressure to a low-pressure area.
2. Convection effects.
3. As the warm moist air rises convectively, it cools, and the moisture is given up in violent downpours.
4. The polar easterlies are cold and dry; the westerlies are warm and humid.

PRECIPITATION

Finally we come to precipitation. To say that precipitation is the most important element that goes into the making of weather and climate would be wrong. All the elements are important. They are inseparably bound to one another. Changes in one element bring about changes in all. However, with certain reservations we *can* say that the pattern of rainfall is the pattern of life—plants, animals, us.

In our investigation of rainfall—where it is and why—we will use as our guide the map of annual rainfall in Figure 13.11. The lines connect points of equal rainfall and are called **isohyets**. Let's choose the 50-cm isohyet as a dividing line and begin our investigation by looking at areas that get less than 50 centimeters of rain a year. These are considered areas of limited rainfall. Later we will look at areas on the other side of the 50-cm isohyet.

There are some pretty bold patterns in Figure 13.11. Focus your attention on the Eurasia–Africa land mass. Note the pattern of limited precipitation extending south and gently

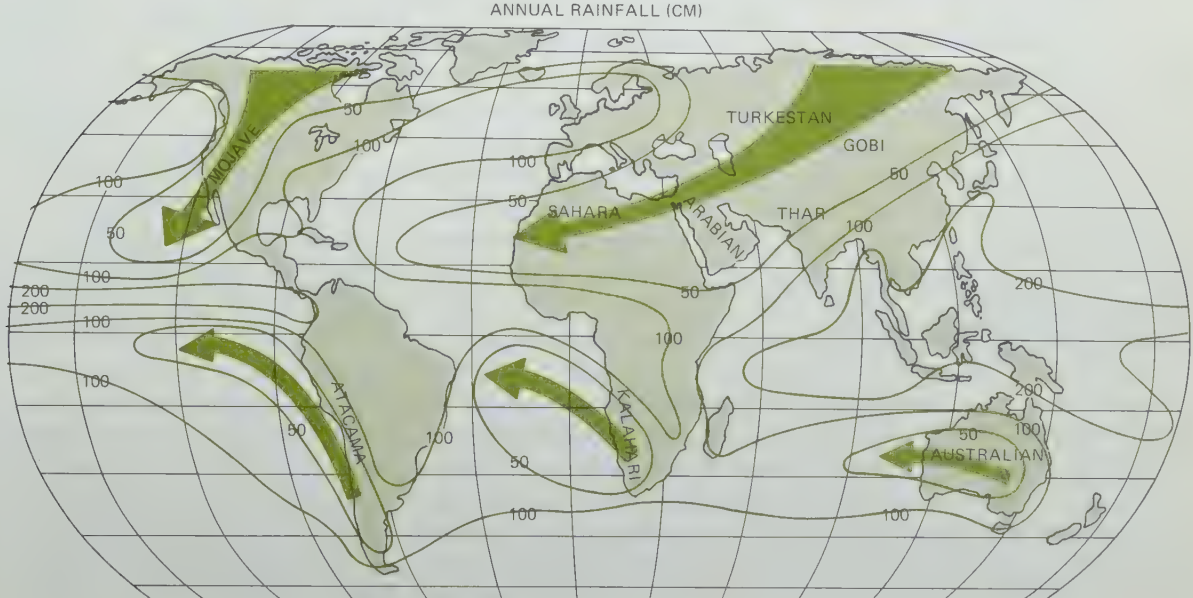
westward from the Arctic edge of Eurasia through the Middle East, turning westward across Africa and extending far out into the Atlantic at about 25°N.

Now look at North America. See the same basic pattern? The area with less than 50 centimeters of precipitation pushes out across the Arctic edge, then narrows rapidly and crosses western America in a north-south manner. Finally there is a westward extension into the Pacific. What are the differences and similarities between the pattern in North America and that in Eurasia–Africa?

In the Southern Hemisphere the same pattern of limited precipitation can be recognized. You might look at Australia first because the pattern there is so striking. The entire heart of Australia is dry. Note that the wedge of dryness reaches across the west coast at about 25°S and extends westward into the Indian Ocean. And you can see the same pattern in South Africa and South America.

How do we explain this pattern? Why do the world's deserts line up on the same side of the continents and at the same latitude? Why do the tongues of limited rainfall extend over the ocean? Why are there dry areas in the interior of the continents? How do we explain the spread of limited precipitation along the Arctic edge and across the Pole? Only controls on a global scale could produce such a consistent pattern. Let's see how these global controls work.

Figure 13.11 Earth's graceful pattern of dryness and wetness is shown on this map. Of the environments shown in Figure 13.1, (**a**), (**b**), and (**c**) are found in the areas covered by the arrows (under 50 centimeters of precipitation). Environment (**d**) is found in areas of heavy rainfall.



The desert maker. If you look along the 25° latitudes on a physical map of the world, you will find the subtropical deserts. You have heard of some of them. The important ones in the Northern Hemisphere are the Mojave in the United States, the Sahara in Africa, and the Arabian and Thar in the Middle East. In the Southern Hemisphere they are the Atacama in South America, the Kalahari in South Africa, and the Great Australian. All are situated along the subtropical high. Is this a coincidence? Or does the great gear wheel of weather have something to do with desert making? It does, and how!

As you learned earlier, the antitrades feeding into the subtropical highs from above are dry. The moisture was dropped in the doldrums. This is part of the reason why the subtropical highs are desert makers. Another and more important reason is that air sinking down toward a subtropical high gets compressed and therefore warms up. With warm air above and cooler, heavy air near Earth's surface, there can be very little overturning of the air. The surface air cannot rise. Gravity will not let it. Because of this condition, few clouds are formed and very little rain falls.

As the trade winds sweep out from the land over the adjacent oceans, they take with them the desert-making controls: warming air and stable conditions. The shape of the dry wedge defined by the 50-cm isohyet demonstrates this flow. Note particularly the pattern in the North and South Pacific off the coast of California and Peru.

Middle-latitudes drylands and polar edge. Look at Figure 13.11 again and note the areas of limited rainfall to the north and east of the Sahara and Thar. These huge islands of dryness are too far north to come under the control of the desert maker. For convenience we will call one of the areas the Turkestan Desert, although it is really made up of many small deserts. At about the same latitude, but hundreds of kilometers to the east, are other very dry areas, the biggest one being the Gobi Desert.

What causes these dry areas? If the subtropical high is not the cause, what is? The answer is obvious if you study the rainfall map. These deserts are in the belt of the stormy westerlies. But there is a great distance between the Atlantic, the major source of moisture (water vapor), and Turkestan. Moisture is given up bit by bit over the 6000-kilometer journey. By the time the air masses reach the Turkestan and Gobi areas, the stormy westerlies are not too stormy. They're all stormed out.

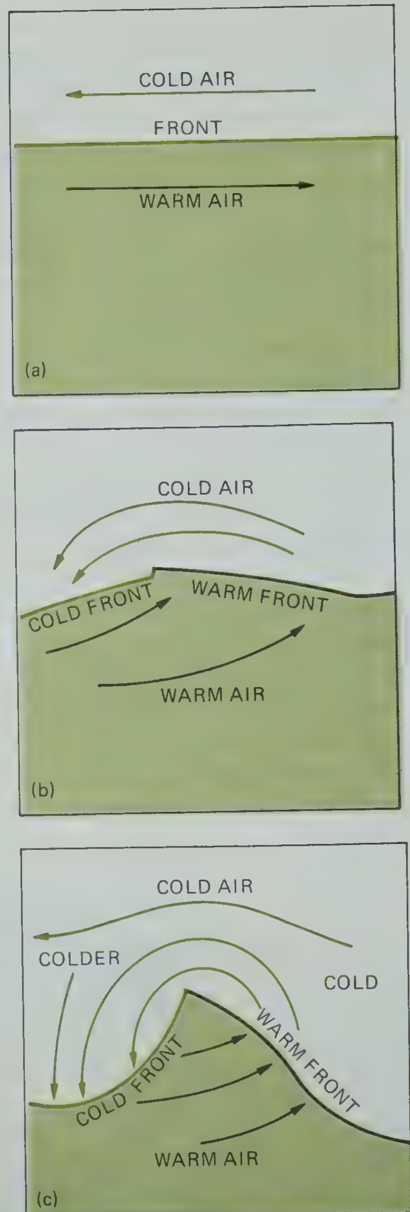


Figure 13.12A In part (**a**), the cold and warm air are separated by a stationary front. The two bodies of air do not mix. In part (**b**), a wavelike disturbance develops along the front and the cyclone is born. In part (**c**), the storm intensifies. The next stage is represented by part (**a**) at right.

The explanation for central Asia holds for central North America. There is one exception: The western edge of the area of limited rainfall in North America is close to the source of moisture, the Pacific Ocean. Then why not more rainfall? The reason is that the Sierra Nevada, the Cascades, and other ranges along the western edge of the continent form a barrier to the eastward flow. The moist wind from the Pacific is pushed up by the mountains. The lifting causes the air to cool rapidly, and as a result a great deal of rain condenses out and falls on the windward (west) side of the mountains. Annual precipitation there can be 150 to 250 centimeters or more. On the downwind (east) side of the mountains, the descending air is compressed and warmed. This air is already dry, having given up its moisture on the windward side. The warming further decreases the possibility of rain, since warm air can hold more moisture. Thus the precipitation on the downwind side is limited to about 10 to 13 centimeters.

Across the Arctic edges of North America and Eurasia stretches another broad band of limited rainfall. The Arctic Ocean is very near. However, it is not a good source of moisture. The cold Arctic air cannot hold much moisture. Therefore the Arctic edge doesn't receive any more rain than the Sahara Desert.

Middle-latitude cyclone. So far we have discussed two causes of rainfall. Rain falls on the windward side of mountains when moist air is lifted by the mountains—for example, on the western edge of North America. At the equatorial regions, rain falls for a different reason: moist air there rises because it is heated. There are many other causes of rainfall, but we will discuss only one more—the middle-latitude cyclone, the weather-maker in the latitudes where most of us live (Figure 13.12 A and B).

In the middle latitudes there are some striking contrasts in air masses. For example, air originating over the bleak cold plains of central Canada and Alaska is cold and dry, and air originating over the waters of the Caribbean is hot and moist. When the cold dry Canadian air mass meets a warm moist Caribbean air mass invading from the south, a **frontal surface** develops between them. The situation is similar to that shown in Figure 13.10. At first it may be a stand-off. The front separating the two air masses may not move noticeably. It is a **stationary front**. But sooner or later, a wavelike disturbance develops along the stationary front. At this moment the middle-latitude cyclone is born (Figure 13.12A).

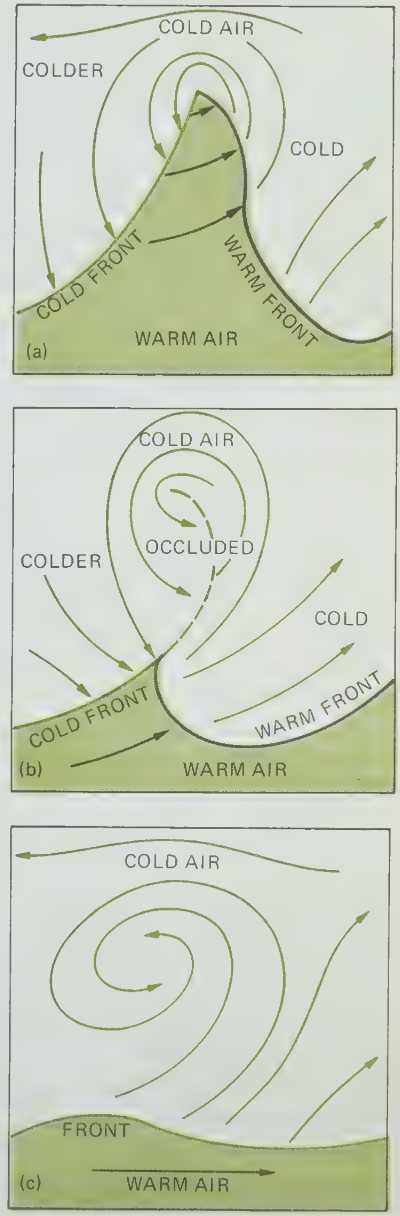


Figure 13.12B In part (a) the storm reaches a peak. Because the cold front moves faster than the warm front, it catches the warm front and lifts it up, producing an occluded front, as shown in part (b). Eventually all the warm air is lifted up and the storm dies, as shown in part (c).

The first sign of the coming storm is decreasing atmospheric pressure (a "falling barometer"), a few clouds, and the development of a counterclockwise flow of air around the low-pressure center. Where the cold air pushes beneath the warm air and lifts it abruptly, a **cold front** is formed. In another sector of the storm, the warm air advances over the cold air, forming a **warm front**. The counterclockwise circulation intensifies, and clouds and precipitation reach a maximum development. The storm is now at its peak. At this stage the storm may measure 1500 kilometers in diameter and reach up to 10 to 13 kilometers. These storms move about 30 to 50 kilometers per hour in a west-to-east direction as great whirlpools in the gigantic river of the westerlies. In time the storm weakens, the aggressive cold front overtakes the warm front and pushes it up. This is called the occluded stage (middle drawing in Figure 13.12B). Finally the warm front is completely overtaken and all the warm air is lifted up. The cyclone dies. It normally takes three to five days to complete the cycle. So ends the history of a middle-latitude cyclone, our weather maker. It is responsbile for the precipitation of the middle latitudes that you see on your rainfall map.

Cyclones are related to a very fast, narrow stream of air called the **jet stream** (Figure 13.13). We don't fully understand the relationship yet, but we know it's a close one. Jet streams flow along a winding path in a generally west-to-east direction at altitudes of 10 to 12 kilometers. The center of a jet stream may reach speeds of about 450 kilometers per hour. Under certain conditions the jet stream develops loops, reaching as far south as 20° and as far north as 45°. Eventually the loops separate from the main flow. They become warm highs and cold lows at a high altitude.

The looping jet stream is very important in distributing heat in the atmosphere. The excessive heat of the tropics is transported to the polar regions by means of the jet stream. The jet stream also moves cold polar air to the tropics. What would Earth's climate be like if the jet stream did not exist? Certainly the tropics would be even hotter and the polar regions would be even colder.

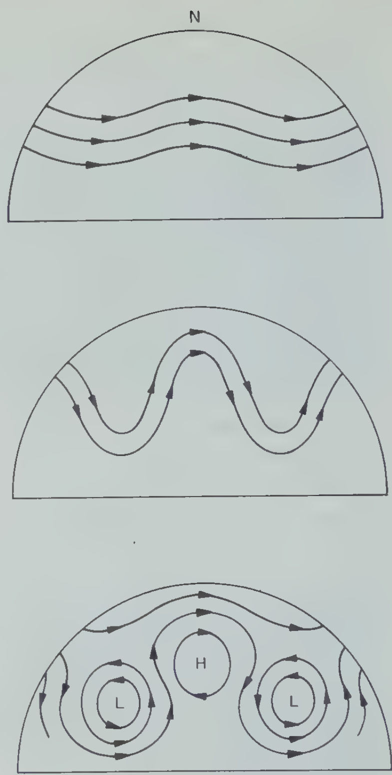


Figure 13.13 The normal jet stream (top) sometimes develops loops (middle), which eventually become high and low centers.

CHECK YOUR FACTS

1. Why are many deserts located at the same latitude?

2. Why do the areas defined by the 50-cm isohyet extend out over the oceans?

(1) (1) **ANSWERS** / Check Your Facts

1. In these latitudes, there is very little overturn and therefore few clouds and little rain.
2. Because the humidity pattern is carried in this fashion by the trade winds.

APPLYING WHAT YOU HAVE LEARNED (2)

1. Look at Figure 13.1. On the left are shown four very different environments. **A** shows the environment of the Arctic and the edge of the Arctic. It is very cold and windy in winter, mild in summer. **B** shows a middle-latitude dryland in the interior of a continent. In winter it is continuously cold. In summer it is hot during the day and cold at night. **C** shows a desert. There is no seasonal variation in temperature—always hot days and cold nights. **D** shows a lush forest typical of the warm, rainy tropics. On the right of Figure 13.1 are shown the kinds of shelter built by the nonindustrial people who live in these environments.

Why are there such different shelters for the different environments? Where do the people get the materials to build these shelters with? What are the advantages of these shelters? What are the disadvantages? Would you be happy living in them?

2. Compare these shelters with the houses or apartment buildings we live in. How do we keep warm in winter and cool in summer? Where do we get the materials to build our dwellings with? Suppose that in a skyscraper that is covered largely with glass and has no windows that can be opened, the air-conditioning system or the heating system broke down. Would it be comfortable inside?

Who pollutes the planet more—industrial people or nonindustrial people?

(2) **ANSWERS** / Applying What You Have Learned

1. (a) See Commentary, p. T16. This introductory discussion is based on these questions. (b) No, at least not at first. You would have to get used to the simple way of life and do without all the modern conveniences you now take for granted.

2. (a) By heating. (b) In some cases, by air conditioning. (c) From many different sources, involving many different industries. (d) No, it would be very uncomfortable. The building depends completely on heating and air-conditioning. It is entirely unrelated to the natural environment. (e) Industrial.

KEY WORDS

weather (p. 264)
climate (p. 264)
greenhouse effect (p. 265)
isotherm (p. 266)
tropical zone (p. 269)
polar zone (p. 269)
temperate zone (p. 269)
isobar (p. 270)
intertropical convergence zone (p. 271)
equatorial low (p. 271)
doldrums (p. 271)
trade winds (p. 271)
subtropical high (p. 274)
westerlies (p. 274)
polar easterlies (p. 275)
isohyet (p. 276)
frontal surface (p. 279)
stationary front (p. 279)
cold front (p. 280)
warm front (p. 280)
jet stream (p. 280)

Figure 14.1 The rocks of the Colorado Plateau are basically flat-lying, as can be seen in the Grand Canyon.

Introductory Demonstration

This demonstration will impress your students with the rate at which parts of the crust are being elevated today and how this kind of change might affect an area in a relatively short time, geologically speaking. From a 10-ft length of two-by-four you can cut pieces of wood 42mm by 95mm in cross section. Have the piece cut into 25-mm, 250-mm, and 2500-mm lengths. Place the 25-mm piece on the floor at the front of the room.

Now inform your students that in one area of southern California, Earth's crust is rising the length of the 25-mm piece each year. Next, place the 250-mm piece on the floor next to the 25-mm piece. Ask students to estimate the length of time it represents (10 years). Finally, stand the 2500-mm piece on end next to the other two pieces. It will represent the increase in elevation that will take place in 100 years at the rate of 25mm (roughly an inch) per year. After some discussion, have students calculate how much the land would rise in 1,000 years, in 10,000 years, in 1 million years. In the discussion that follows, stress that Earth's surface is constantly changing and that even mountains do not take forever to form. So as not to give a wrong impression of rates of uplift, point out to students that the rate used in this demonstration is high, even for the more active areas of Earth's crust. Also, point out that most parts of Earth's crust are stable and are not undergoing any uplift.

chapter 14

The Surface on Which We Live

As recently as thirty or forty years ago, the average American was raised, educated, and buried not very far from where he, and his parents before him, were born. If a man was born in a small town in central Iowa, for example, it is quite likely that his travel consisted of short trips to surrounding communities or to a nearby city (Des Moines or possibly even Chicago). To such a person, surface features such as mountains or plateaus (broad, high, flat areas) could be only things that he read about in books.

Today, however, with so many highways, cars, and airplanes, more and more people—young and old alike—are traveling to different parts of the country and the world and are seeing, for the first time, parts of Earth's surface that are totally different from the part on which they live.

THE AMERICAN LANDSCAPE

On an automobile trip from our location in central Iowa to western Colorado, a distance of approximately 1600 kilometers, a person would see many different landscapes. From central Iowa to the Missouri River, which is the western border of the state of Iowa, he would travel through slightly hilly country not very different from the country around his own town. The topography (shape of the land) would be much the same, corn would still be the most common crop, and the trees and other types of vegetation would make him feel at home. (1)

From the Missouri River westward, however, he would begin to feel less at home. The surface he would see is flatter, and there are fewer trees growing on it. Our traveler would also notice that there are not nearly as many farm animals to be seen. He might wonder about this. Why, he might ask, are there fewer trees and why are the farms and villages so far apart? And why is the land so flat in western Nebraska?

After traveling hundreds of kilometers over what might have seemed like monotonous plains, our traveler would see a blue haze rising in the distance. As he got closer he would see that the haze is actually a series of deep canyons and mountain peaks. This is a third type of topography! Our make-believe traveler has not even reached western Colorado yet, and already he has traveled through three large areas that differ from one another in very noticeable ways. If we were to extend our traveler's trip, how many other types of landscape would he see? Why is the landscape of one region so different from that of another? Were they formed by the same processes? To answer these and other questions that have to do with the shape of Earth's surface, we need to start by looking at a big section of the land surface, if not the entire surface. Since we are most familiar with the United States, we will concentrate our efforts on that part of Earth. For a starter, let's look at some photographs taken from space and from them put together a picture of the surface.

Figure 14.2, taken from an Apollo spacecraft in orbit around Earth, shows the shape of part of the North American continent. If you study photographs from space such as this, as well as photographs taken from high-flying aircraft, you would see that at least three kinds of landscapes can be (2) identified even from great altitudes. One type of landscape appears on the photographs as long, relatively narrow ridges. (3) What word do we use to describe such areas? Do these areas

(1) The landscapes discussed here are both located in the physical region (physiographic province) called the Interior Lowlands. The differences pointed out are largely due to climate. In central Iowa, average annual precipitation is 75-80 cm (30-32 in.), in western Nebraska it is 37.5-50 cm (15-20 in.).

(2) The new Earth Resources Technology Satellite (ERTS) now orbiting Earth at an average altitude of 950 km (595 miles) is providing scientists with far more information than did the satellite from which the photograph in Figure 14.2 was taken.

(3) Most students think of areas of great altitude (e.g., the Himalayas, the Sierra Nevada) when they think of mountains. Not all mountains are high (e.g., the Appalachians). Have students check the elevation of some of the mountains in the eastern United States. Mountains are found in areas where internal forces such as uplift or volcanism prevailed over erosion.

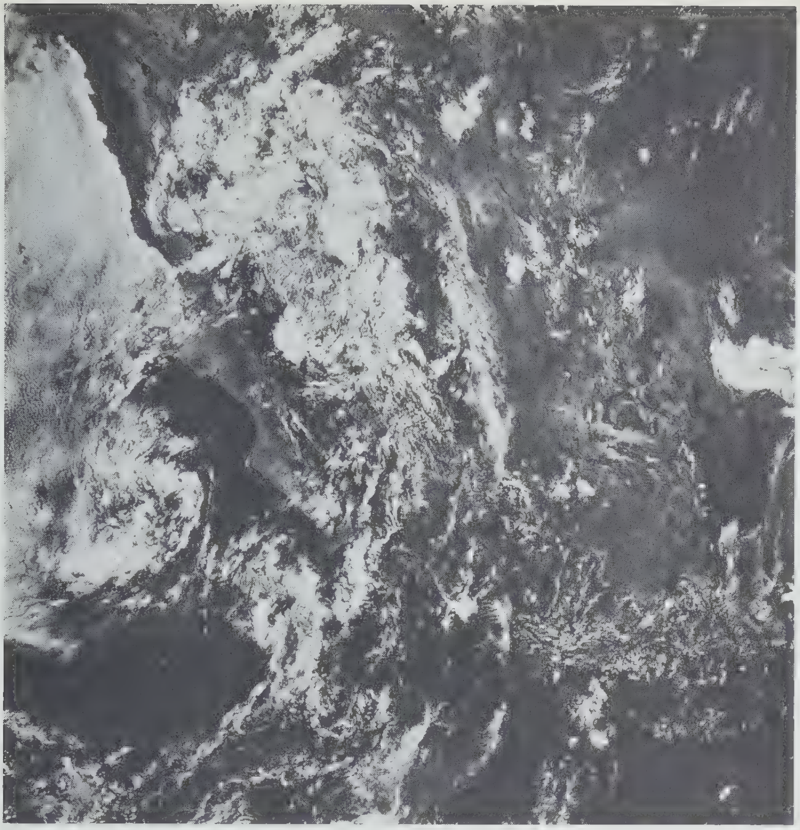


Figure 14.2 Part of the North American continent can be seen in this photograph taken from space. The long strip of land at the center left is Baja California, Mexico. The small dark patch near the upper left corner is the Salton Sea, California. This area is shown in greater detail in the photograph opposite the title page of this book, a photograph also taken from space.

have any particular orientation? The general location of the major **mountain areas** of the United States is shown on Figure 14.3A.

Another major type of landscape consists of very extensive, more or less flat areas. One of these areas extends along the Atlantic and Gulf coasts, another in a north-south direction across the middle part of the continent. If you live (4) in either of these areas, but especially the one that extends from Canada in the north to Texas in the south, you know that these areas are called **plains**. The major plains areas of the United States are shown in Figure 14.3B.

(4) Major plains areas coincide roughly with areas of crustal stability. In general, plains areas are areas which have not been greatly elevated and consequently not deeply eroded. The relief (difference in elevation) is generally less than 100 meters.

The third type of surface area that can be quite easily identified from photographs or by direct observation from high flying airplanes is somewhat smaller in area than the first two types discussed. Like the plains area, this type of area appears from high altitudes to be relatively flat and to have (5) fairly sharp boundaries. Two of these areas, which are called **plateaus**, are in the western part of the United States, and one is in the eastern part. The location of plateaus in the United States is shown in Figure 14.3C.

(5) Plateaus are elevated plains. The principal difference between plains and plateaus is in the amount of relief. Deep valleys and canyons are characteristic of plateaus. Plateaus are usually underlain by horizontal or near-horizontal layered rocks.


COAST RANGES
CASCADES
NORTHERN ROCKIES
SIERRA NEVADA
SOUTHERN ROCKIES
APPALACHIANS
A


CALIFORNIA TROUGH
GREAT PLAINS
INTERIOR LOWLANDS
COSTAL PLAIN
B

Figure 14.3 The mountain areas (A), plains (B), and plateaus (C) of the United States.

If we combine the information given in Figures 14.3A, B, and C, we would get the map shown in Figure 14.4. You will notice in looking at Figure 14.4 that although a large part of the surface area of the United States can be subdivided into mountains, plains, and plateaus, there are also fairly large areas that do not fall into any of these categories.

If you examine in more detail the areas that make up the blank spaces on Figure 14.3, you will find that they have some of the characteristics of one or more of the three major types of landscapes, and in addition have some characteristics that are pretty much their own. Thus, they can also be identified as distinct areas. More detailed examination of each of the areas classified as mountain, plain, or plateau areas would show that each of these areas also has features that set it apart from other similar areas. The Appalachian Mountains, for example, are a series of long ridges and valleys, whereas the Sierra Nevada is a very large block of Earth's crust that has been tilted upward along a great fault at its eastern edge. In addition to the shape of the surface, features such as the structure and age of the rocks in an area are also important in drawing the boundaries of areas of different types of topography.

(1) Many years ago, scientists recognized that the continents could be divided up into a number of regions with similar topography, structure, and so on. Such regions have come to be known as
(1) physiographic provinces.

(1)

Figure 14.4 If we combine the three previous maps, we obtain this map showing the main features of the United States.

CHECK YOUR FACTS

1. What are three major kinds of landscapes in the United States?

2. Where are the major mountain areas of the United States?

3. Where are the plateaus of the United States?

4. How do the Appalachian Mountains differ from the Sierra Nevada?

(1) ANSWERS / Check Your Facts

1. Mountains, plains, and plateaus.
2. There are three main mountain areas in the country. One is located near the eastern margin of the country extending from Maine to Alabama. The second area is to be found in the western part of the country extending from Canada to New Mexico. The third area is along the western margin of the country. It extends from Canada to southern California.
3. The Appalachian Plateau is located west of the Appalachian Mountains in the states of New York, Pennsylvania, Ohio, West Virginia, Kentucky, Tennessee, and Alabama. The Colorado Plateau covers a large area in northern Arizona and New Mexico, western Colorado, and southeastern Utah. The Columbia Plateau is located in Washington, Oregon, and Idaho.
4. The Appalachian Mountains consist of a series of more or less parallel ridges and valleys that are underlain by folded and faulted crystalline and sedimentary rocks. The Sierra Nevada, by contrast, is a great block of granitic rocks, 644 km

WHY DO LANDSCAPES DIFFER?

We have seen in our very incomplete examination of the surface of the United States that landscapes do vary. Closer examination would show that they vary considerably. But why? Why do they vary?

Does climate affect landscape? We have noted that at three different locations in the United States, well-developed plateaus occur. To obtain an answer to the question, "Does climate affect landscape?", we might compare two of these plateaus, the Appalachian Plateau in the east and the

long and 64 x 129 km wide, which has been tilted westward. The eastern slope of the Sierra, along which extensive faulting has occurred, is very steep.

Colorado Plateau in the southwest. Let us look first at the Appalachian Plateau. The rocks in this area are sandstones, (2) limestones, and shales; and they occur in nearly flat layers. As we look more closely at the landscape of the Appalachian Plateau, we see that it is not a continuous, more or less smooth surface. Rather, it is an area that has been cut up by numerous streams forming a certain kind of drainage pattern. In Figure 14.5 the more or less flat top of the plateau can be seen, but even more noticeable is the deep valley that has been cut into the plateau. Another noticeable feature of this landscape is the abundance of vegetation. Does this also suggest that the soil cover in the area is fairly thick? And what does it suggest about the climate of this region?

(2) Have students locate the two plateaus on a physiographic diagram. Also, have students look up the elevation and the mean annual precipitation in each of the areas.

Let us look next at the Colorado Plateau. In this plateau, as in the Appalachian Plateau, the rocks are basically flat-lying. This characteristic of the rocks can be clearly seen in Figure 14.1. As far as the structure of the rocks is concerned,

Figure 14.5 The more or less level surface of the Appalachian Mountains can be seen in the distance.

therefore, there are few differences. But what about the kinds of materials present at and near the surface in this area? Upon closer examination we find that the sedimentary rocks exposed along the valley (canyon) walls are also sandstone, shale, and limestone. Basically no difference. But surely there are some differences. The following activity is designed to shed some light on the problem.

Figure 14.6 Part of a map of the Colorado Plateau.

activity 14.1 Examining the Colorado Plateau

Examine Figure 14.1. There is one very striking difference between the area shown there (the Colorado Plateau) and the Appalachian Plateau. What is it? What factor is responsible for this striking difference? Examine Figure 14.6, which shows part of a topographic map of the Colorado Plateau. Are there (1) as many streams in this area as there are in the Appalachian Plateau? Does your observation support your conclusion about the cause for the striking difference? How do you think the amount of precipitation received in the Colorado Plateau compares with that received in the Appalachian Plateau?

(1) There are relatively few permanent streams in the Colorado Plateau. From an examination of the photographs of the two plateau areas, students should be able to draw conclusions about the amount of soil present in each area. A discussion of soil formation would be in order here. Precipitation in the Appalachian Plateau varies from 75 to 125 cm (30-50 in.) per year. In the Colorado Plateau it varies from 25 to 50 cm (10-20 in.) per year.

Figure 14.7 A typical landscape in central Iowa.

We have seen that flat-lying sandstones, limestones, and shales underlie both the Appalachian and Colorado Plateaus. We also know that both areas are high compared to surrounding areas. Has climate been an important factor in shaping the landscape of these two areas?

If climate is the answer, or at least part of the answer, are there other factors involved? Is the type of leveling process that is most active in an area an important factor? Or is it the materials (soils, rocks, vegetation) at and near the surface that are most important? Or are there other factors that control or affect the formation of the landscape in an area?

Rock structure—what influence on landscape?

In our discussion of the role climate plays in shaping the landscape, we found it helpful to compare two regions. If the approach worked for climate, perhaps it will serve to illustrate the role rock structure plays in shaping the land. Let's see if it will.

In order to get as much contrast as possible, it would be good to select areas in which the climate is not very different but the rock structures are strikingly different. Can we find two such areas? The answer is yes, and without too much effort. For area 1 we will use an area in central Iowa. For area 2 we will use an area in the Appalachian Mountains of Pennsylvania. In area 1 the earth materials at and near the surface consist of a relatively thin covering of soil resting on flat-lying sandstones, limestones, and shales. Figure 14.7 shows a typical landscape in central Iowa. In area 2 the soil cover is also quite thin; but in contrast to the area in Iowa, the sedimentary rocks beneath the soil are sharply folded. Figure 14.8 illustrates well the valleys and ridges of the Appalachian Mountains. Although it is not possible to tell from the photograph what the underlying structure is, detailed

Figure 14.8 Typical Appalachian valleys and ridges can be seen in this view of Trevorton, Pennsylvania. The ridges shown here are formed by resistant rock layers that are part of a syncline (large downfold).

examination of the rocks would show that resistant sandstone beds form each of the ridges, and underlying each of the valleys are less resistant shales and limestones.

Examination of Figures 14.7 and 14.8 tells us that there are marked differences in the shape of the land in these two areas with similar climatic conditions. To what can we credit these differences? The answer seems quite clear—it is due, in part, at least, to the structure of the rocks.

activity 14.2 *Comparing Iowa with the Appalachian Mountains*

Figures 14.9 and 14.10 show sections of topographic maps of (1) **the areas we have been discussing. Observe the stream pattern in the two areas. How do they differ? Make a sketch of each pattern. What is the determining factor in the formation of** (2) **the stream pattern in each area?**

(1) The stream pattern in Iowa is the kind that is found in areas where bedrock exercises little or no control over the direction of valley growth. A pattern of this type is called *dendritic.* In the Appalachian Mountain area tributary streams flow more or less parallel to one another and at close to a right angle to the main stream. Bedrock control is due to the erosion of folded sedimentary layers of differing resistance to weathering. Such a stream pattern is called a *trellis drainage pattern.*

(2) In any discussion of the development of a trellis stream pattern, students will speculate as to why the main stream cuts across the ridges and valleys. The most reasonable explanation is that in fairly recent time (late Tertiary) the main streams which now cut across the structure in the Appalachians started flowing on a low plain formed by erosion. This plain was then slowly uplifted. During the uplift, the main streams maintained their courses and gradually cut down through the folded layers they encountered.

The role of time in landscape development. The Colorado River is a swirling, muddy stream. Its high energy and its load of rock debris are the power and the tool with which it is eroding the bottom of its valley. Even as we watch it, the valley is slowly changing. It is being deepened, and

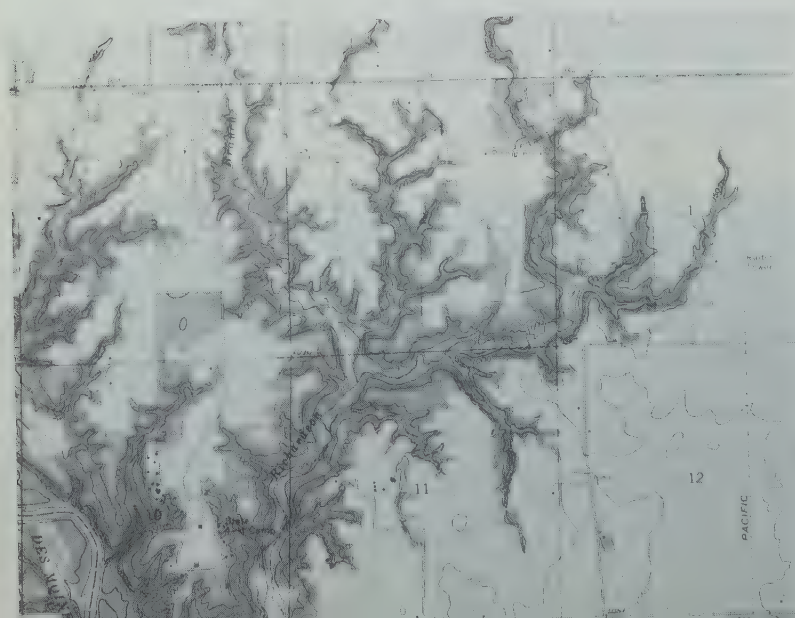


Figure 14.9 The stream pattern developed along the Des Moines River is the most common type of stream pattern.

Figure 14.10 The stream pattern shown here is characteristic of parts of the Appalachian Mountains. It is not a common type of stream pattern.

in many places its sides are being worn back by weathering and the effect of gravity and sheetwash. Nearly everywhere along the river's course, elevations are decreasing. Because the energy of the stream is decreasing, we can predict the future of the valley and the region the river flows through.

As the valleys of a main stream and its many tributaries change in size and shape, the landscape as a whole must change. It is obvious that as time goes on, the amount of material that has been removed from an elevated region will be greater. We can measure the amount of sediment that the Colorado River carries past a point in the Grand Canyon during a certain interval of time. The rate turns out to be about 10,000 tons per hour. Then we calculate how much the area drained by the river and its tributaries is now being lowered by erosion. The answer is: a very few centimeters in a thousand years. In the Appalachian Plateau the rate is probably ten times as great. Can you explain how erosion can be more rapid in a region where the bedrock is covered with a blanket of soil?

We can predict the future of the Colorado and Appalachian Plateaus, but we will never know whether we are right. Millions of years must pass before leveling processes will have changed the landscapes to greatly different ones.

Can physical processes alone shape the land?

We have seen the effect of rock structure, of climate, and of time on landscape development. Are there places where the effect created in the landscape by a physical process is more striking than the effect of rock structure?

A process that can change the landscape in a very dramatic way is volcanism. By burying landforms under lava and ashes, it creates striking new landforms. The power of lava to change a landscape can be seen in southeastern Washington, where lava flow after lava flow poured out, burying hills and even mountains to create the high, broad Columbia Plateau (Figure 6.14). The sort of landscape the lava covered can be seen all around the plateau. Here the landscape and the structure certainly had no effect on the process of volcanism. The new landscape was the result of a physical process alone. But as soon as lava stops flowing, weathering and erosion begin to attack the new landforms. The Columbia Plateau is being eroded in the same way as the Colorado Plateau is.

Volcanoes are very vulnerable to attack by erosional processes. Streams cut valleys into the sides of the volcanic cones. If the volcano has been built up high enough, glaciers may form and begin to gnaw at it. Volcanic landforms, like others we have investigated, eventually disappear.

Wind action is a process that can also produce distinctive landscapes, mainly by depositing sediments that conceal the underlying structures. Wind does not normally have nearly as much energy as running water, and requires special conditions to be a really effective gradational agent. Wind depends on other surface processes, such as weathering and the work of streams, waves, and glaciers, to provide material that it can move. However, when there is a supply of fine, dry sediment (1) available, wind can blow sand into dunes in much the same way that it makes snowdrifts. Where would you expect to find large areas of dunes? Where have you seen dunes? Can you explain why they are there?

(1) Many people believe, probably as a result of seeing too many French Foreign Legion movies, that the wind is a more important agent in shaping the land than it actually is. Dunes, for example, make up a relatively small part of most deserts, and most unusual topographic features are the result of erosion by agents other than wind.

Besides removing sand from loose deposits and piling it up nearby, wind carries finer materials far away. It takes fine soil particles from the drier parts of the Central Plains and carries them as far away as the Atlantic Coast or over the ocean. In this way, wind is lowering the land.

Movements of the crust alter the surface. In August 1959, the Yellowstone Park region was shaken by an earthquake. The quake shook loose an estimated 80 million

Figure 14.11 The Sierra Nevada, one of the most impressive mountain ranges in North America, is the result of changes that have occurred in the fairly recent geologic past. **(2)**

tons of rock and soil. This material swept down a steep mountainside, destroying everything in its path and damming the Madison River. Examination of the surrounding area revealed that the earthquake had been caused by movement along the Hebgen Fault northwest of Yellowstone Park. The land on one side of the fault moved upward relative to that on the other side, thereby forming a cliff several meters high. This cliff will disappear in a relatively short time, geologically speaking, unless there is additional movement along it. Is there any evidence to indicate that movement such as that which occurred along the fault near Yellowstone Park is repeated over and over again? The answer is yes. The evidence is to be found in the east face of the Sierra Nevada in California (Figure 14.11). The east face of this impressive mountain range is a tall, steep face resulting from repeated movement along a fault over a long period of time. Movement of the crust has certainly altered the landscape in California, and there is no reason why it could not further alter the landscape in the Yellowstone Park area.

(2) Intensive faulting, uplift, and tilting along the eastern side of the Sierra Nevada began about 2.5 million years ago. One estimate, based on radiometric dating and other evidence, suggests that uplift of the Sierra Nevada took place at an average of 300 m of uplift per million years. Have students figure out how much uplift this would be per year.

Detailed surveying in the Tehachapi Mountains in southern California shows that uplift of that area is taking place at an impressive rate of 150m per century. At other locations in southern California, local uplift rates as high as 26 mm per year have been measured.

What makes landscapes? You have learned that landscapes are the result of numerous factors (climate, rock structure, processes, earth movements, and time). With as many factors as are involved, it can be assumed that there can be as many different types of landscapes and landscape features as there are combinations of these factors.

Because the Earth is a dynamic planet and change is constantly taking place, it is reasonable to assume that landscapes once formed are not permanent features of Earth's surface. Geologists believe that large parts of the Rocky Mountain area were plains areas in fairly recent geologic time. Is it reasonable to expect that they might become plains areas again? (1)

> Time is a sort of river of passing events,
> And strong is its current;
> No sooner is a thing brought to sight
> Than it is swept by and another takes its place,
> And it too will be swept away.
> Marcus Aurelius Antoninus (A.D. 121–180)

(1) It is indeed reasonable to expect that the Rocky Mountains will be leveled by erosion once again.

If students gain nothing else from this chapter, it is hoped that they will take with them the concept that practically all of the landscapes that exist today are the result of changes which have occurred in the recent geologic past. The Sierra Nevada and the glaciated areas of the northern United States and Canada are good examples of landscapes that have resulted from change in the last few million years. The everlasting hills are not everlasting!

CHECK YOUR FACTS (2)

1. What are some differences between the Appalachian Plateau and the Colorado Plateau?
2. What are some differences between Iowa and the Appalachian Mountains?
3. At what rate is the area drained by the Colorado River and its tributaries being lowered?
4. What is a common feature of land that was once covered by glaciers?

(2) **ANSWERS** / Check Your Facts

1. The Appalachian Plateau is considerably lower than the Colorado Plateau; it has much higher precipitation [75-125 cm (30-50 in) versus 25-50 cm (10-20 in)] and supports more vegetation; generally speaking, it is more dissected.
2. The elevation and relief in central Iowa are considerably below those in the Appalachian Mountains. The most significant difference between the two areas is in the structure of the bedrock. In central Iowa, bedrock consists of essentially horizontal sedimentary rock layers. In the Appalachian Mountains the sedimentary layers which make up the bedrock are sharply folded and faulted.
3. 10,000 metric tons per hour.
4. Glaciated areas are commonly poorly drained, contain abundant lakes, ponds, and bogs, and have a layer or layers of glacial till over the bedrock.

APPLYING WHAT YOU HAVE LEARNED (3)

1. Some important differences between the three major kinds of landscapes in the United States—mountains, plains, and plateaus—are size of area and topography. But there are other differences also. What are the other differences?
2. What things determine the type of landscape that is present in an area?
3. Once formed, do landscapes remain the same? Explain.

(3) **ANSWERS** / Applying What You Have Learned

1. Other differences are: plains and plateaus are commonly underlain by essentially horizontally layered rocks, mountains are not; mountain areas are commonly elongated, plains and plateaus

4. Explain the role that a physical process such as glaciation might play in shaping the land.

5. Have any large scale landscape changes taken place in recent years in the area in which you live? If not, have there been smaller scale changes that you and/or others have observed? Might these smaller changes some day bring about major changes?

KEY WORDS

mountain area (p. 285)
plain (p. 285)
plateau (p. 285)

are not; and mountains always exhibit a much greater degree of dissection. Plains differ from plateaus in that they usually exhibit much less relief.

2. Factors which determine the type of landscape are the bedrock and the physical processes that are most active in the area.

3. No. Landscapes are constantly changing. Volcanism, uplift, erosion, and deposition, to mention just a few, are active processes on the earth today. As a result of the action of these and other processes, landscapes continue to evolve.

4. Glaciation can alter the surface of the land by deepening and widening canyons in mountainous areas or it can have a pronounced leveling effect in areas which were covered by continental glaciers. Volcanism can similarly bring about greater relief by building mountains or it can level an area through the buildup of layer after layer of lava.

5. The purpose of this question is to get students to think seriously about change in their own areas. Relatively few areas experience large-scale changes such as those brought about by volcanism or faulting, but all areas exhibit smaller changes that occur regularly. Stream valleys, coast lines, road cuts, and even school yards are good places to observe small-scale changes.

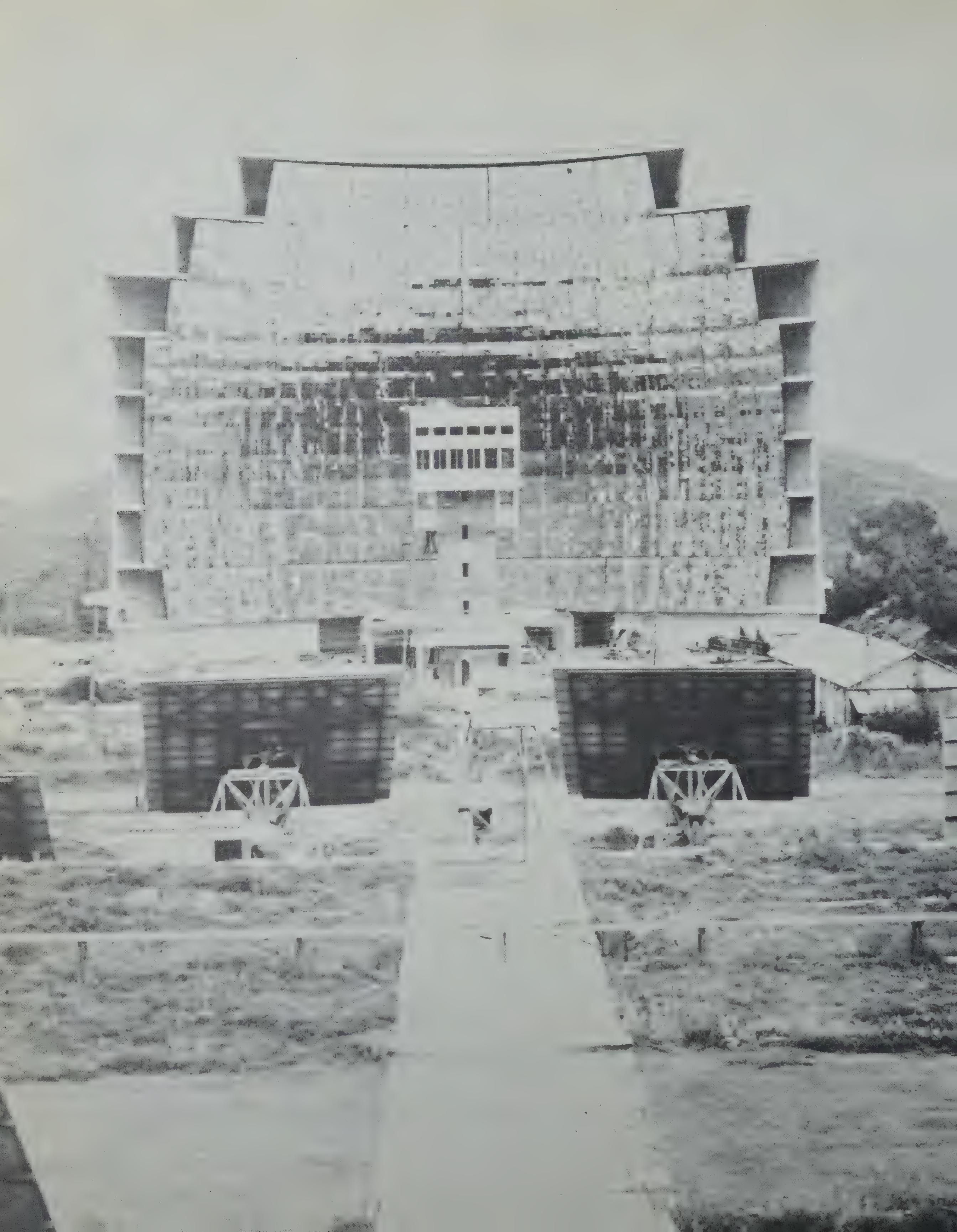


Figure 15.1 This reflector focuses sunlight to a point located in the white structure seen in the center. At the focal point, the temperature is high enough to melt steel.

Introductory Demonstration

Show the filmstrip "Mineral Resources—Metals and Non-metals" (W), start the discussion, and get out of the way.

chapter 15

The Future of Our Natural Resources

Mankind seems to have thought, without much thinking, that Earth's mineral and fuel resources will last forever. Today we know better. They are going too fast, and most are nonrenewable. "Nonrenewable" means that nature took such a long time to create them that if we use them up, they will be gone forever as far as man is concerned.

There are two problems. One is that we are using our resources too fast, and the other is that there are more and more people to use them.

POPULATION

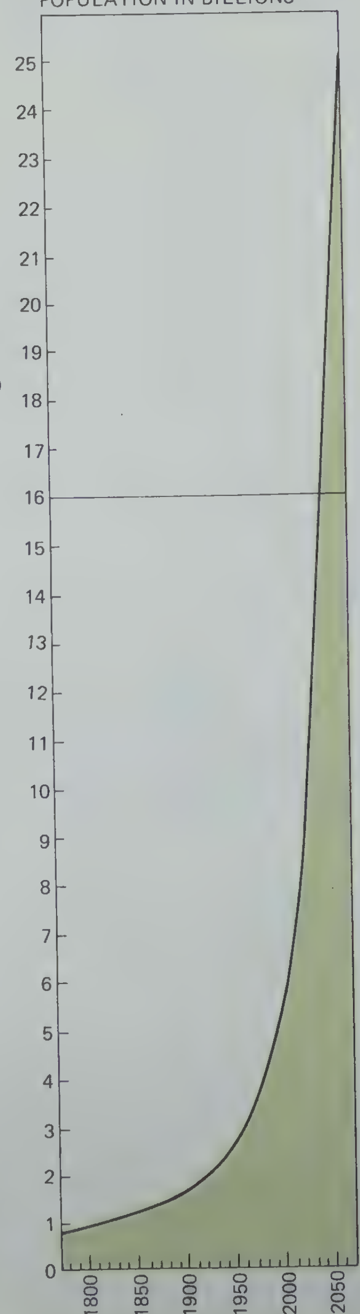
The population of our world is now over 3.5 billion. At the present rate of increase, the population will double in 35 years (Figure 15.2). A hundred years ago it took about *twice* as long to double the world population, and that population was only about *half* as large! The mathematicians call this kind of doubling a "geometrical progression." An example of such a progression would be if you put a grain of rice on one square of a checkerboard (with a total of 64 squares), 2 grains on the next square, 4 grains on the third square, and so on. You are doubling each time. How many grains would you have on square 64? This would make a fine activity for you and your class, but some of the other students would object when the school disappeared under a rice pile. That 64th square would take several hundred times this year's world rice crop! (1)

A population does not increase as dramatically as this because there are natural controls on all living things to prevent such growth. For example, foxes could cover Earth; but they would run out of rabbits, mice, and whatever else they eat long before the increase became very large. But man controls nature more than other animals do. Still, he can push Mother Nature only so far and then she will strike back.

Even if our present population doubling rate just stayed the same, 1000 years from now there would be about 2000 people for each square meter of Earth's surface—land *and* sea! Either we will limit our population or, eventually, nature will do it. And nature may not be very pleasant about it.

How much of our increasing use of minerals and fuels in the United States is due only to more people being around? Probably about 40 percent. What about that other 60 percent of the increase?

Figure 15.2 This chart represents what would happen if there were no controls at all on population growth.



HOW DO WE USE OUR NATURAL RESOURCES?

Metals. Our natural resources are mainly used for two things: material (cars, cans, etc.) and energy (gasoline, electricity, etc.). Since 1940, we have used more metal than was ever used in the whole history of Earth before that. Most of the best deposits of many metals have probably already been found. Many are in danger of being used up completely! We

can't wait for more, since the formation of most ore bodies involves processes that take millions of years. Some experts predict we will be all out of tin, tungsten, and mercury by 2000. You won't be very old in 2000, and we would like to leave you some.

Can we mine regular rock and get metals? Sure. In every 100 tons of the average igneous rock there are 8 tons of aluminum, 5 tons of iron, and small quantities of other elements. Can't we just depend upon science and engineering to figure out a way to get these metals out of the rock and make them available? We can probably figure out a way, but it will cost much, much more than present mining. And where will we get the energy to mine such large amounts?

Metals such as copper give a different picture. The largest mines in the United States are now taking out ore with less than one ton of copper for each 100 tons of rock. When these low-grade ores are gone, whether in 50 years or 500, we will have to be as careful with copper as we are now with gold. One suggestion is that every bit of equipment containing such metals as copper, tungsten, lead, and tin be rented instead of bought. That way we could be sure we get it back for recycling instead of allowing it to be thrown away.

(1) The quantity of rice on the sixty-fourth square would be about 180 billion metric tons (about 400 trillion pounds). The entire checkerboard would have twice that amount on it. The 1970 world rice crop was about 306 million metric tons.

Figure 15.3 Strip mining often leaves stagnant pools of water and other ugly scars on the land.

Collecting scrap metal and recycling is only a partial answer. If we someday have to depend on scrap metal and common rocks for our metals, the United States would probably be able to have as much metal in use by individuals as we had a hundred years ago. This won't be enough. But at least recycling would help clean up our country.

In the past, mining and the processing of ore have commonly been done without concern for the environment. The mine dumps of waste material have left ugly scars across the countryside. Open mine pits are ugly holes. Now some companies are planting trees on the dumps and landscaping them. The open pits can be made into recreational lakes and some can be filled with rock that has to be moved to get at the ore. However, many open pits are still being left just as they are (Figure 15.3). Gases from plants where ore is processed have killed vegetation in many places, but this need not happen today. We now have the technology to clean up the gases, although it is certainly not being done everywhere. Like anything else, the trouble is that it costs money.

Fossil fuels. Energy may be more of a problem in the near future. Already we have power failures in areas of large population concentration. Most energy in our country comes from the use of fossil fuels. We call them "fossil" fuels because we believe that gas and oil (petroleum) originate from microscopic plants and animals buried among the grains of sediment in the seas, and we know that coal (Figure 15.4) comes from plants. Since petroleum is used for about 75 percent of the total energy produced in our country and 99 percent of the transportation, let's take a closer look at how long we can keep on using it as we now do.

In 1940 we used about 4 million barrels of oil every day in the United States. By 1970 this had increased to 14 million barrels a day. We have had a fairly regular 7 percent increase in use every year. Our total use in 1970 was over 5 billion barrels. Of these, 4 billion were produced in the United States. The whole *world* in 1970 used 15 billion barrels. Thus, the United States, with about 6 percent of the world's people, uses over 30 percent of its petroleum. We won't be able to go on like this. Not only will other countries use a bigger percentage, but there isn't enough petroleum. In fact, many countries will never be large consumers of petroleum because by the time they might reach that level of industry, there won't be enough left for them.

Figure 15.4 The dark area at the bottom is a coal bed.

Some careful estimates have been made of how many barrels of oil still remain in the ground. Most of this oil, like that part you use in a car as gas, is many tens of millions, often hundreds of millions, of years old. A general estimate is that there are about 4100 billion barrels left. Most of this is oil we don't even know about yet—we just believe it's probably there. In the United States we probably can't count on more than 200 billion barrels being left in the rocks. For us, that means that at our present rate of use, the oil in the United States will be gone in about 50 years. But we keep using 7 percent *more* every year and if we continue, it could be gone in closer to 20 years.

The entire world could be out of oil by the year 2015. **(1)** That's not much time. Somebody had better start doing something soon. It's like getting smart; the longer you wait, the harder it is.

There are no easy ways to slow down a civilization or its birthrate. But there are places to start. Since one half of the petroleum used in the United States goes for automobile transportion, think what would happen if all cars were half as large and burned half as much gas. Less steel, less copper, less oil, less pollution. What if estimates of oil and gas are too low, and we really had enough to last 200 years? Big deal. There's too much future time for mankind. We have to be concerned, even though our present overuse may not greatly affect you or me. We shouldn't even be burning oil and gas. They are more valuable for their chemicals than for their heat energy. People **(2)** a few hundred years from now may shake their heads in astonishment, anger, and disbelief—"They actually used to *burn* gas and oil!" The worst thing about the situation is that no worldwide body exists to even begin planning for the future.

But we must have energy. We have to heat our homes, light our nights, and travel efficiently, unless we are content to burn wood and live more primitively. Living more primitively is attractive to some individuals, but it's never attractive to nations and their governments. So what is the answer to our coming fuel problems?

Other energy sources. Solar energy is an energy source large enough to fill some of our future needs (Figure 15.1). The problem is it would require so much metal and other material to construct solar heat gatherers that the energy and material input may not justify what we could get out. Also, we would have to cover a great deal of the land surface with the solar gatherers and construct electrical storage sta-

(1) The basic idea you should get across is that the use of minerals and fossil fuels cannot, absolutely cannot, continue indefinitely at anything near the present rate. The supply of metals, oil, and coal is finite, and new formation of them is far slower than the production of new persons to use them. If one regards the future of the human race in terms of thousands or millions of years, which few planners do, the era of extensive use of natural resources may be only a moment in time.

(2) If petroleum comes to be in short supply, as it will, the price will probably increase. If some widespread alternative energy source for heat is not developed, this economic factor will begin to influence our country. If it were to cost a few hundreds of dollars more per year to heat a home in the northern cities (such as New York or Detroit) or thousands more for factories there, perhaps large industries would cease to develop in those climates. Possibly the large northern population centers would slowly disappear.

tions for energy use during the night. It doesn't seem to be a practical way out for us.

Water power to turn turbines and produce electricity provides about 2 percent of the world's energy. We could dam more rivers, but not enough. We would only drown more valleys for very little gain. The power of tides is used in a few places to provide energy, but tides won't solve the energy problem either.

Some people have suggested that we use Earth's internal (1) heat to make electricity. Steam from volcanic and hot spring areas is now being used at places in Italy, New Zealand, Mexico, Iceland, and Russia. In California, steam from hot springs is used to generate electricity. But there are very few areas in the world where enough heat is near enough to the surface to make its use practical. Perhaps we could drill deep wells and pump water down them. When the water turned to steam, expanded, and came to the surface, we could use the steam to run turbines and produce electricity. This may be practical for part of our future needs.

What will we be using for energy in the middle of the 21st century? The only answer that seems possible is nuclear (atomic) power. Right now electricity is being produced from atomic power plants. The process now used is **nuclear fission**, or the splitting of the nuclei of certain radioactive isotopes. One isotope that can be fissioned is uranium-235. The problem is that less than 1 percent of Earth's uranium is uranium-235 and over 99 percent is the isotope uranium-238. We can't keep using the present process for our future energy because there isn't enough uranium-235 to last more than a few tens of years.

Scientists are now working hard to make a **breeder reactor** in which the radioactive process produces nearly as much fuel as it consumes. The abundant uranium-238, as well as some other isotopes, can be converted to other radioactive isotopes that can be used in the fission process for energy. But uranium-235 is still required as a starter, and we are using it pretty fast. The big problem is to convert to the breeder reactor before we completely use it up. The United States is trying very hard to have our first breeder reactor in use by 1980. If we don't make it by then or shortly after, we may be in trouble. One of the important problems with the present reactors is that they tend to pollute our planet. They have a (2) lot of heat to do away with and, worse, radioactive material is sometimes dumped into the atmosphere or streams. All radioactive products are potentially dangerous to humans, so this waste must be dealt with carefully. But still, knowing

(1) It may be possible to get significant amounts of electricity from crustal heat. A current plan calls for the drilling of two wells to 15,000 feet. Cold water would be pumped out down one well and allowed to heat up as it migrates through a porous rock, such as sandstone, to a second well. The steam coming from the second well would be used to run a turbine and produce electricity. Some people are optimistic about this plan, but more appear to be pessimistic.

(2) Heat is not necessarily a pollutant. If the heat could be used in industry or in homes, that problem might be solved. The main factor preventing this to date seems to be finding an effective way to transmit the heat. Because of the possibility, no matter how slight, of a nuclear accident in these power plants, they are built away from metropolitan areas.

the future of fossil fuels, there isn't any other practical worldwide thing to do except encourage research in nuclear power production. We must stop the pollution of nuclear power plants but we cannot stop nuclear power.

One other nuclear process is being worked on. This is **nuclear fusion**, or the joining of nuclei of atoms to form other nuclei with the release of large amounts of energy. So far the reaction has been uncontrolled—it is the reaction used for the hydrogen bomb. Hydrogen isotopes are fused to produce helium and energy. If we can control this reaction, there is an amount of energy in the hydrogen of one cubic kilometer of sea water to equal that produced by all the oil the world ever had! And no radioactive waste is produced. Maybe we can control fusion one day, maybe not.

CHECK YOUR FACTS

(3)

1. Can we get metals from regular rock rather than from metal-rich ores?

2. What percentage of the world's petroleum is used by the United States?

3. About what percentage of the petroleum used in the United States goes for automobile transportation?

4. Do fission power plants pollute the environment?

APPLYING WHAT YOU HAVE LEARNED (4)

1. Why are some fuels called "fossil fuels"? If oil is forming today in sediments, why can't we just wait around until it's ready to use and get it out?

2. Well over 95 percent of the transportation in the United States (planes, cars, trains) depends upon petroleum. If we run out, how will we transport food, manufactured goods, and people around the United States?

3. Why must we be careful about using up uranium-235 in our present atomic power plants?

KEY WORDS

nuclear fission (p. 304)
breeder reactor (p. 304)
nuclear fusion (p. 305)

(3) **ANSWERS** / Check Your Facts

1. Yes, but it will cost a lot more in terms of energy input and dollars than we can now afford.
2. About one-third.
3. Approximately one-half.
4. Yes, but probably not to a great degree. Many people are justifiably concerned and wish to restrict the construction of more plants. This may be a good idea, especially since the present plants use too much of ^{235}U which will soon be in short supply. Research in nuclear production of energy should be supported and, of course, the radioactive and thermal pollution problems have to be solved.

(4) **ANSWERS** / Applying What You Have Learned

1. Coal and petroleum are the fossil fuels, so-called because they are formed from the remains of organisms that lived million of years ago. The average age of most petroleum is millions of years. This is too long to sit around and wait for it.
2. Recommended as a discussion question. With a little guidance, a very lively discussion will result.
3. The supply is limited, and ^{235}U is needed as the starter for breeder reactors. We must therefore hoard our supplies of ^{235}U until we have something to take its place.

unit four

Beyond Earth

Can you imagine what other civilizations have looked into a sea of night and asked the kinds of questions that we ask? What other civilizations have walked and worked on a moon hundreds of thousands of kilometers away, or thought of life and conditions on other worlds? What other beings have measured energies equal to that of a billion hydrogen bombs or distances of billions of light-years? Are there others like us, who study messages from pulsars, talk of giants and dwarfs, and determine the chemical composition of distant objects by merely analyzing the light they emit? Who else can think about a region of space, closed into itself, where gravitation is so strong that even light cannot escape from it? Who else can imagine a universe like this?

Figure 16.1 No one knows yet how this riverlike feature on the Moon was formed.

Introductory Demonstration

To most of us "bigness" suggests dimensions, such as diameter, circumference, or radius, but apparently how "big" is the Moon? How many Moons could you extend end to end like beads on a string reaching from the horizon in the east all the way across the sky to the horizon in the west? This demonstration must be performed when the Moon is visible during the day. Consult your calendar or newspaper for such times. Have a student hold an aspirin tablet at arm's length. He will find that he can cover up the Moon with the aspirin (or a penny, a piece of chalk, a pencil, and so on). The Moon isn't very big after all! One aspirin tablet has an angular width of $\frac{1}{2}^{\circ}$. Knowing the number of degrees from horizon to horizon (180°), calculate how many moons would fit in this amount of sky? Surprising, isn't it! Do you think the Moon's size will be the same at different elevations? What about the "big" orange harvest Moon? This is a dramatic point to make your students imagine that 360 Moons fit from horizon to horizon.

chapter 16

The Moon— One Giant Leap For Mankind

In the past, man looked upon the Moon with awe. Some people thought that it had special powers over them. Some thought of the Moon as a god and worshipped it just as they did other gods.

It was not until the time of Galileo (1564–1642) that man first began to have a scientific approach to the study of our satellite. In the first telescopic studies of the Moon, Galileo drew pictures that showed that the Moon has similarities to Earth (Figure 16.2). We have made great progress since those early days! Space exploration in the last ten years has added greatly to our knowledge of Earth's environment and of the entire solar system, including the Moon. Although we have

merely glimpsed the environment of space, at least we have expanded our horizons beyond the confines of Earth.

The success of the Apollo missions in putting men on the Moon and the exploration of space by satellites are among the most spectacular achievements in the history of mankind. Man's visit to the Moon has indeed been one "giant leap" for mankind.

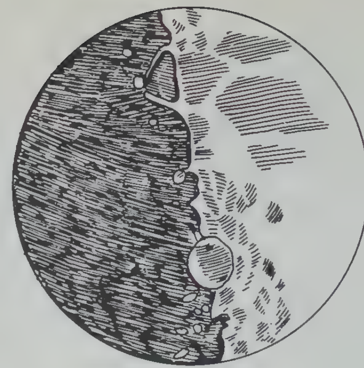


Figure 16.2 This sketch of the Moon was made in 1610 by Galileo, the first man to study the Moon through a telescope.

THE MOON'S MOTIONS

The Moon, like the Sun and other stars, is always changing its position in the sky. From Earth, all the heavenly bodies seem to move around us once a day. We seem to be located at the center of a gigantic hollow sphere that rotates around us once a day. The stars appear to be glued to the inside of this sphere. You know of course that this is not the true picture. The skies do not rotate around us once a day. Instead, Earth rotates on its axis once a day. Earth spins like a top, carrying

(1) Start a discussion by asking questions like: How do you know that Earth rotates and that the heavenly bodies do not really rise in the east and set in the west?

Figure 16.3 These photographs show, from left to right, the shape of the Moon 3, 5, 11, and 14 days after it reappears. It then grows dark again, with the dark spreading in from the right, so that the crescent points in the opposite direction.

us with it. This spinning is what causes the heavenly bodies to appear to move around us. (1)

But the Moon has another special motion of its own. It seems to crawl from west to east against the background of the stars. (It is not fixed to the gigantic sphere.) It returns to the same position in the stars every $27\frac{1}{3}$ days, and, as it moves against the stars, it appears to change shape. In about two weeks, it changes from a round disk to a half-disk to a crescent. It becomes such a thin crescent that it almost disappears. Within a day or two, it reappears as a crescent, and after another two weeks, it has regained its round shape (Figure 16.3).

The Sun, too, changes its position against the stars. Many changes we see in the sky result from the complicated motions of the Moon and Earth. To understand the Moon's behavior, the most important thing to know is that the Moon moves in a roughly circular orbit around Earth. We say "roughly circular" because the Moon's orbit is not a circle but an **ellipse**, which is like a flattened circle. Some ellipses are very flattened and long. Some ellipses are not very flattened—that is, they are almost circular (Figure 16.4).

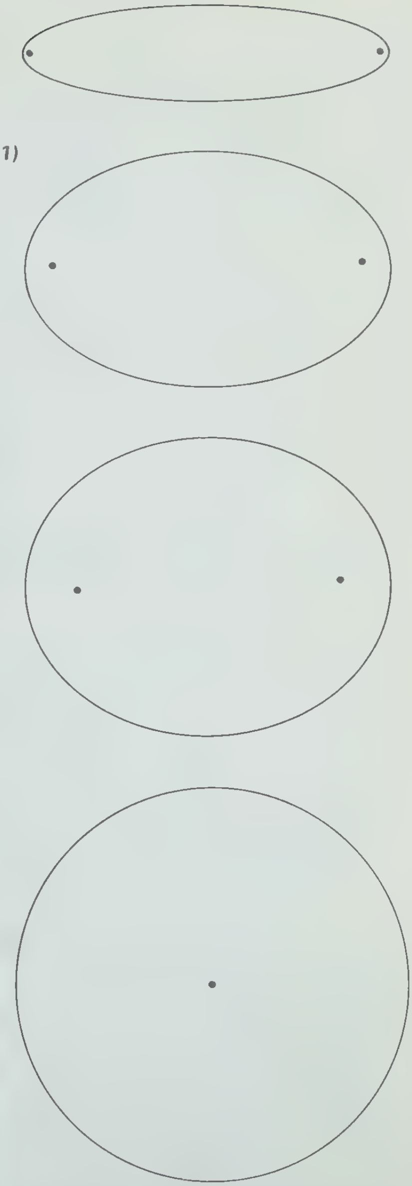
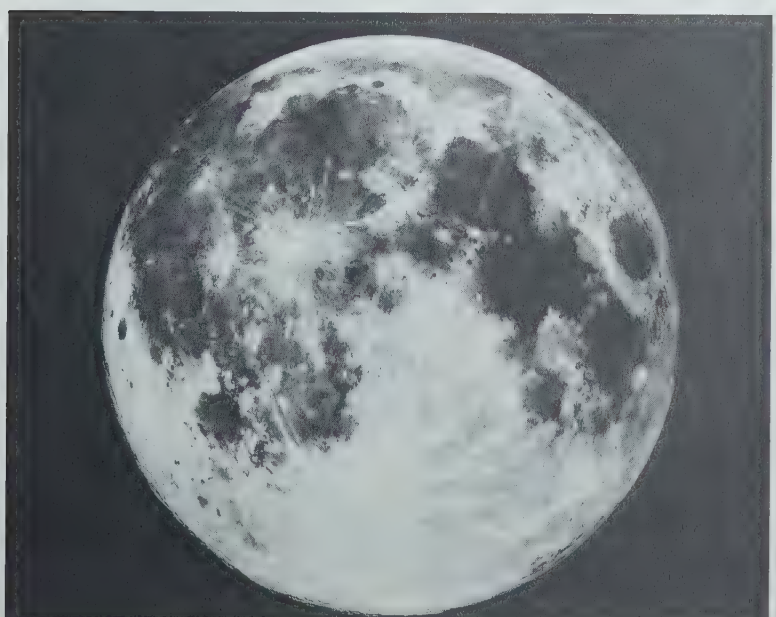


Figure 16.4 The two points inside the ellipse are called the foci (singular: focus). When a body moves in an elliptical orbit around a much more massive body, the massive body is located at one focus. The circle is an ellipse whose foci are the same point.

Gravitation. What keeps the Moon in orbit around Earth? You probably already know the answer: the **gravitational**



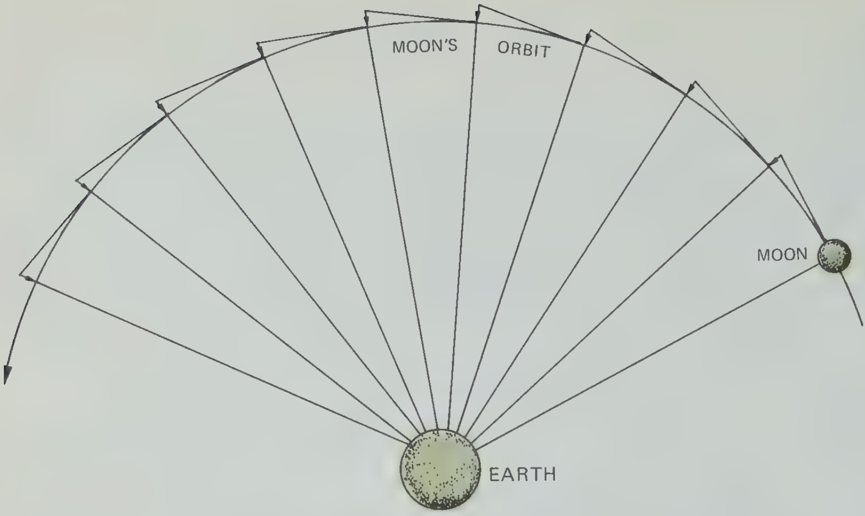


Figure 16.5 The gravitational force between Earth and the Moon pulls the Moon away from a straight-line path.

force. Gravitational force acts between every pair of bodies(1) in the universe, not just the Moon and Earth. The more massive the bodies are and the closer together they are, the stronger is the gravitational force pulling them toward each other. Without gravitational attraction to keep the Moon in orbit around Earth, the Moon would move off in a straight line and get farther and farther away from us (Figure 16.5).(2)

The Moon pulls on Earth just as hard as Earth pulls on the Moon, as shown in Figure 16.6. However, because the Moon is much less massive, it is moved by Earth much more than Earth is moved by it. The situation is much like a very heavy man and a skinny boy balancing on a seesaw (Figure 16.7). The balance point is much nearer the heavy man. In the case of Earth and the Moon, the balance point actually lies inside Earth. The point is called the center of mass of Earth and the(3) Moon (it is labeled B in Figure 16.13). Both Earth and the Moon revolve around this point, just like the way the man and the boy swing around the seesaw's pivot point. This motion of Earth and the Moon has an important effect in producing the tides of the ocean, as we shall see later.

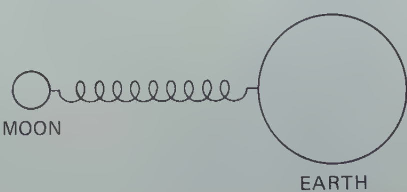
The Moon's phases. The way the Moon appears to change shape is one of the most fascinating things about it, and one of the easiest to understand. First, we must remember that the Moon does not shine by its own light, as does the Sun. The Moon can only reflect the light of the Sun; we can see only that part of the Moon's surface on which sunlight is falling. The relation between Earth, Moon, and Sun is constantly

(1) The gravitational force between two bodies varies inversely with the square of the distance between those bodies.

(2) Ask this question: If the Moon did get farther away from Earth, how would its gravitational attraction affect Earth? Answer: The farther away, the less the gravitational force. (If twice as far away, it would be one-fourth as much.)

(3) Ask this question: If the Moon's mass were the same as Earth's, where would the center of mass of the system be? Answer: Midway between the two bodies.

Figure 16.6 The gravitational force between two bodies is mutual. That is, the two bodies pull on each other with exactly the same force.



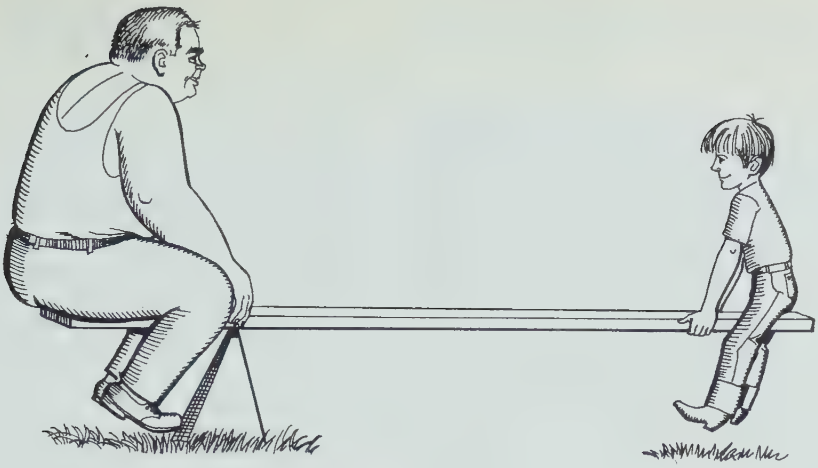
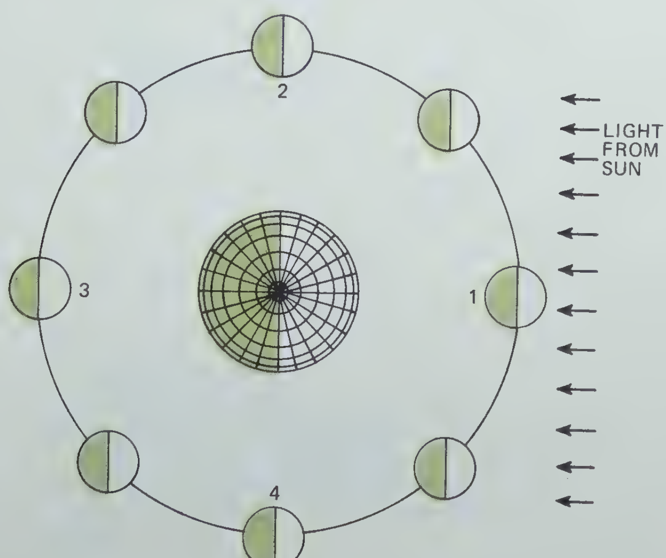


Figure 16.7 The balance point between a fat man and a skinny boy is closer to the man than to the boy.

changing as the Moon moves in its orbit. In Figure 16.8, we show only Earth and the Moon. The Sun is much farther away, but the arrows show the direction its light comes from. When the Moon is very nearly between Earth and the Sun at position 1, the bright half of the Moon is turned completely away from Earth, and so the Moon is almost invisible. When the Moon

Figure 16.8 From position 1, the Moon grows fuller and fuller until it reaches position 3, as shown in Figure 16.3.

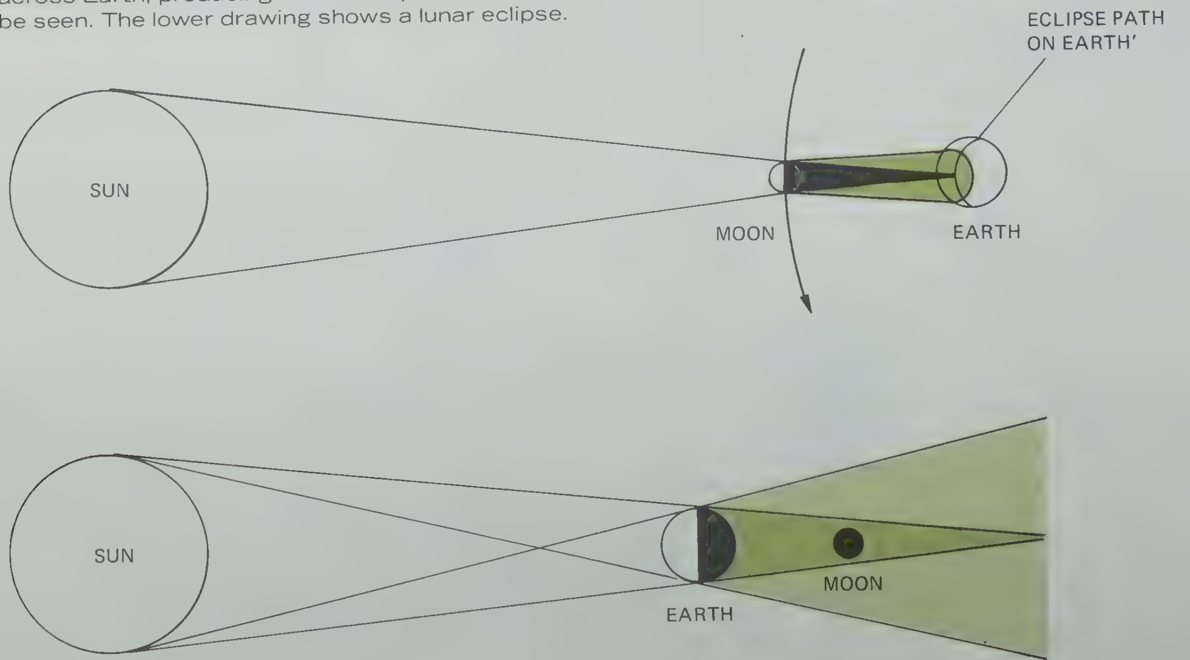


has moved one quarter of the way around in its orbit (position 2), half of the illuminated side is visible from Earth. This position is called **quarter moon**, because the Moon has traveled a quarter of its orbit. At quarter moon, the line joining Earth and the Moon is perpendicular (at right angles) to the Sun's rays, which is also the direction of the line joining Earth and the Sun. At position 3, the Moon has completed half of its trip around Earth. Now all of the bright side of the Moon faces Earth, and we have the **full moon**. The process then reverses itself. Less and less of the bright side is visible, and at position 4, the Moon is only a quarter moon again. Finally the Moon returns to position 1, and is almost invisible. In this position it is called **new moon**. The various different positions (and appearances) of the Moon are called its **phases**.

(1) (1) The angle between Earth, the Moon, and the Sun is different for each phase: at crescent the angle is about 45°, at quarter it is 90°, at gibbous ($\frac{3}{4}$ full) the angle is 135°, and at full it is 180°. The new phase is in the same direction as the sun, and this angle is 0°.

Eclipses. You may wonder why the Moon receives any light from the Sun at position 3 in Figure 16.8. Wouldn't Earth block the Sun's light? Often this happens, and then we have an

Figure 16.9 When the Moon comes between the Sun and Earth (top drawing), the Moon's shadow sweeps across Earth, producing a solar eclipse. From the central, dark part of the shadow, no part of the Sun can be seen. The lower drawing shows a lunar eclipse.



eclipse of the Moon, or **lunar eclipse**, as shown in Figure 16.9. However, the Moon's orbit is tilted (Figure 16.10), so that usually the Moon passes slightly above or below Earth's shadow.

Just as Earth can block the Sun's light from reaching the Moon, the Moon can block the light from reaching Earth. This can happen when the Moon is new, at position 1 in Figure 16.8. It is called an eclipse of the Sun, or **solar eclipse**. For a solar eclipse to happen, the Moon must lie on the line joining Earth (2) and the Sun. Again, because of the tilt of its orbit, the Moon usually misses this line, and solar eclipses are rare but wonder- (3) ful sights.
(4)
(5)
(6)

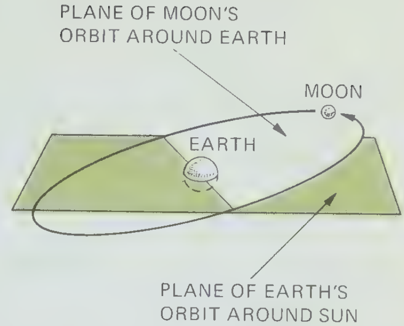


Figure 16.10 The plane of the Moon's orbit around Earth does not lie on the plane of Earth's orbit around the Sun.

(2) When the Moon is only slightly off the line joining the centers of the Sun and Earth, a partial solar eclipse may take place.

(3) When the Moon is at apogee (farthest distance in its orbit) and an eclipse occurs, the apparent size of the Moon will be too small to cover the disk of the Sun. This form of eclipse is called an *annular* (ring-shaped) eclipse.

(4) The Hammond Co. has an excellent overhead transparency on eclipses.

(5) Check an observer's handbook or an *Ephemeris* for the year and note when eclipses of each kind will occur. Make a note of these, and perhaps you can plan a field trip for your class to observe an eclipse.

(6) See ESCP Pamphlet Series PS-9, "Field Guide to Astronomy Without a Telescope," Houghton Mifflin (1971), for additional activities relevant to eclipses.

activity 16.1 *Positions of the Sun, Earth, and the Moon*

Here we will see how the phases of the Moon are determined by the positions of the Sun, Earth, and the Moon. We will also obtain a better understanding of the true motions of Earth, the Moon, and the Sun. Figure 16.11 shows the path of the Moon around Earth over a period of about a month. The positions of the Sun are also shown during this period. The positions shown are the positions of the Sun and the Moon in the sky as seen from Earth, not their true positions in space. The Sun is really much farther away than the Moon. Furthermore, it's Earth that moves around the Sun, not the other way around. Remember that the diagram shows only what we see looking from Earth. Both the Sun and the Moon appear to move counterclockwise. The apparent solar motion is about 30° or $\frac{1}{12}$ of a revolution, per month. Do you see any special meaning to the fraction $\frac{1}{12}$? (7)

Lay a straightedge across the diagram from the Moon's position on May 3 to the Sun's position on the same date. What is the phase of the Moon on this date? Remember that at quarter (8) **moon, the line joining Earth and the Sun must be at right angles** (9) **to the line joining Earth and the Moon. When, approximately,** (10) **will this occur? When will the next full moon occur? We have said that the Moon moves nearly in a circle around Earth. Test this by trying to draw a circle centered at Earth that passes through all the positions of the Moon. What do you conclude** (11) **about the actual distance from Earth to the Moon?**

Where in the Moon's orbit does it travel fastest? Can you (12) **guess the reason for this?**

(7) There are 12 months in a year.

(8) Full moon.

(9) About May 11 and May 25.

(10) About June 2.

(11) It varies.

(12) When it is nearest to Earth (at perigee).

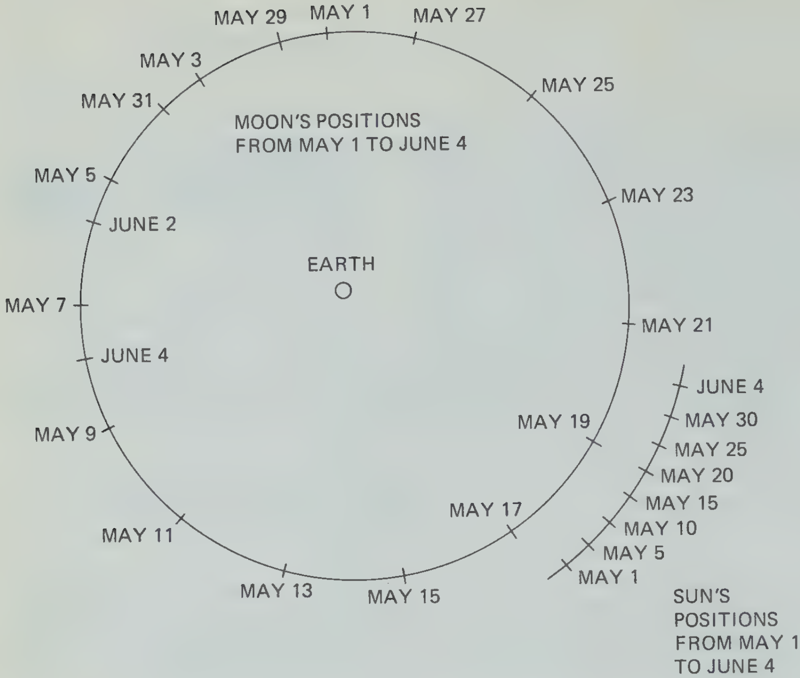


Figure 16.11 This diagram shows the positions of the Sun and the Moon as seen from Earth.

The tides. If you have ever visited the seashore, you have surely noticed that the level of the sea seems to change from hour to hour. Twice a day, the sea rises to a high point, and between these times it sinks to a low. We see this effect by the watermarks on docks and the advance and falling back of the sea along the beach. At any given moment, there are two **high tides** and two **low tides** on Earth. The period between successive high tides is roughly 12 hours, 25 minutes. The total amount of water in all the oceans of the world remains the same, but something makes it rearrange itself. As you probably know, the chief cause of the tides is the Moon. The gravitational pull of the Moon on the ocean makes the ocean rise towards the Moon, producing a bulge in the ocean that is almost directly under the Moon. (1)

(1) The highest tides on Earth are found along the coast of Nova Scotia, Canada, on the Bay of Fundy. Here the variation from high to low tide is as much as 18 m.

Actually there are two bulges in the ocean, one on the side of Earth nearest the Moon and one on the side of Earth farthest from the Moon (Figure 16.12). The bulge on the far side is very puzzling. To understand it, we must remember that Earth makes many motions. One motion is the daily rotation about its axis, point C in Figure 16.13. But remember that Earth must also swing around point B once every month to balance the Moon. This motion causes the ocean on the side away from the Moon to bulge out, producing a high tide there.

Another reason why there are two tidal bulges on opposite sides of Earth is that the Moon attracts the side near it more

strongly than it attracts the side away from it. You can think of the situation like this: The side of Earth nearest the Moon (area N in Figure 16.13) is pulled most toward the Moon, Earth itself is pulled less, and the side away from the Moon (area F) is pulled the least.

The Moon is not the only cause of tides on Earth. The Sun, too, produces tides. Because it is so much farther away than the Moon, it has less effect on the tides than the Moon has. But in a small way it does increase or decrease the Moon's tide-producing effect. When the Sun is lined up with the Moon, they

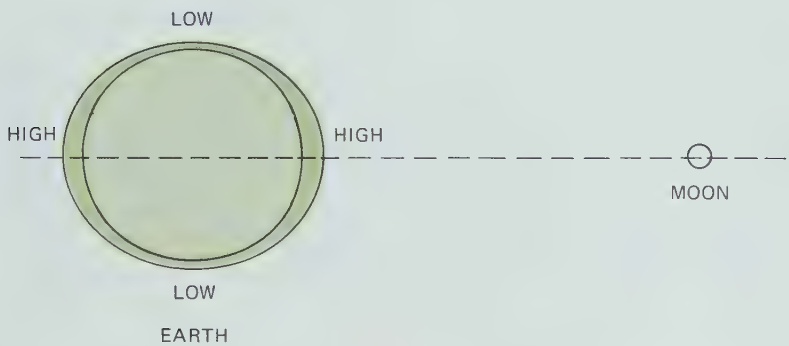
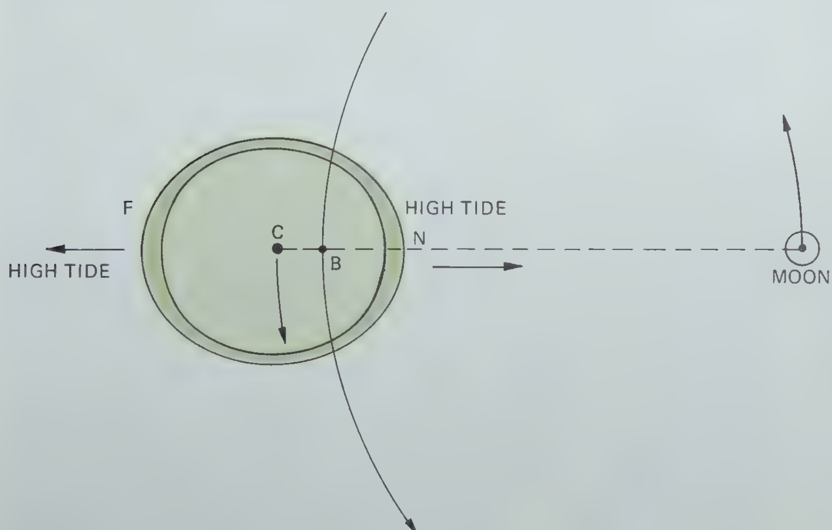


Figure 16.12 There are two high bulges in the ocean. The depth of the water is greatly exaggerated in this diagram.

Figure 16.13 The Moon and Earth orbit around their common center of mass, which is actually located inside Earth (point B).



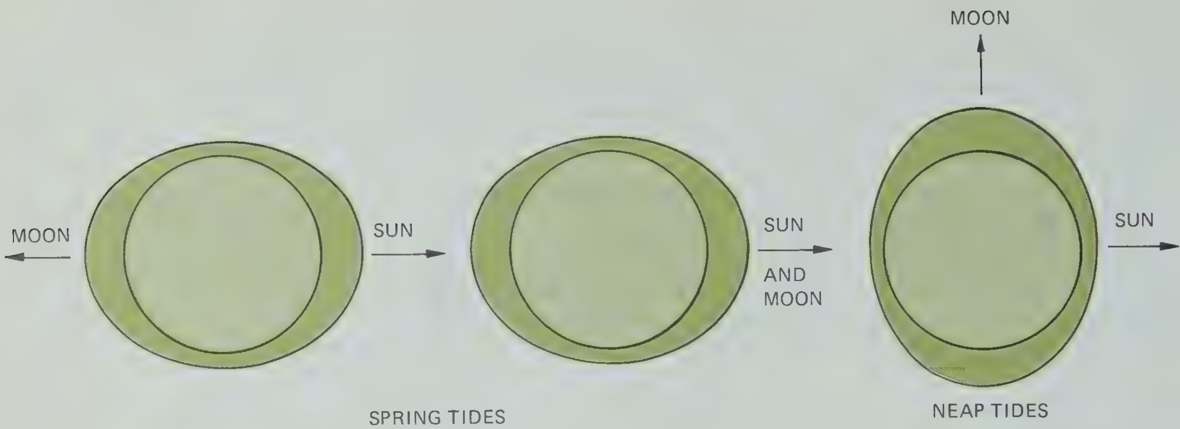


Figure 16.14 Especially high tides, which occur when the Sun, the Moon, and Earth are lined up (left and middle diagrams) are called spring tides. Weak tides, which occur when the Sun, the Moon, and Earth form a right angle (right diagram) are called neap tides.

work together and the tides are especially high. When the Sun, the Moon, and Earth form a right angle, the tide-producing effect of the Sun and the tide-producing effect of the Moon tend to cancel each other, and weak tides are produced (Figure 16.14). Most of the time, the Sun and the Moon do not line up; they pull Earth from different directions.

Can you think of another reason why tides are higher at some times than at other times? (Hint: Think about Activity 16.1 again. What did you learn about the Earth–Moon distance?) **(1)**

Tides also occur in Earth's solid crust, which is somewhat flexible. There are even tides in the atmosphere. Atmospheric **(2)** tides are complex, due to changing weather conditions. But the explanation of all tides is the same, whether in the oceans, the solid crust, or the atmosphere. The cause is the gravitational pull of the Moon, and to a lesser extent, that of the Sun.

You may be surprised to learn that there are tides on the Moon, too. They are caused by the gravitational pull of Earth. As a result, the shape of the Moon is not perfectly round, **(4)** but instead bulges toward Earth. Because the Moon has no oceans, the bulge is not so obvious. The tides on Earth and the Moon influence the motions of both bodies in very complicated, interesting, and not completely understood ways. The tides act to slow down the rotation of Earth on its axis while making the Moon's orbit bigger. In other words, the day is getting longer and the Moon is getting farther away from Earth. But don't worry! Both changes are occurring very, very slowly. You don't have to rush out to buy a slower-running clock, and the Moon will always be around for you to look at.

(1) If the Earth-Moon distance varies, then the gravitational pull on Earth's waters will vary, too.

(2) The gravitational pull of the Moon on the Empire State Building at times raises this structure several centimeters.

(4) Some experts think that the Moon experiences moonquakes (ruptures on its surface) because of Earth's gravitational pull on the Moon.

CHECK YOUR FACTS

1. What are some ways the Moon affects life on Earth?
2. What keeps the Moon in orbit around Earth?
3. Describe the Moon's phases.
4. How many tidal bulges are there on Earth?
5. Does the Sun have any effect on the tides?

(5)(5) **ANSWERS** / Check Your Facts

1. The Moon establishes the month, influences human superstitions, causes tides, lights the night, produces eclipses, is interesting to all people, and slows down the day (rotation of Earth).
2. Gravitational force.
3. See Figure 16.11.
4. Two.
5. Yes, but not as much, because it is so far away.

WHAT'S IT LIKE ON THE MOON?

Next to going there like the astronauts, the best way of studying the Moon is through a telescope. In fact, for an overall view, a photograph taken through a powerful telescope is the best way of getting an idea of what the Moon is like.

Figure 16.15 is a photograph of the Moon taken at quarter phase, and Figure 16.16 is a closeup shot of a crater named Archimedes. In these pictures, we see craters, mountains, and

Figure 16.15 (below left) The ups and downs of the Moon's surface can be clearly seen in the areas near the dark area.

Figure 16.16 (below right) You can figure out some of the history of this part of the Moon's surface.

valleys that appear to be somewhat similar to those on Earth. On Earth there are not nearly as many craters as on the Moon. How do you think the Moon's craters were produced? (Make a guess.) The dark, flat areas on the Moon were once believed to (1) be seas, but today we know they are quite dry and were probably produced by lava flows.

(1) From meteoritic impact and volcanism.

activity 16.2 Studying the Moon from photographs

In Figure 16.15, is the Sun shining from the left or from the right? If you were standing on the shadow line separating the dark and light halves of the Moon, where would the Sun appear to be in your sky? Where would you have to stand in order for the Sun to be directly overhead?

From the Moon, Earth would go through phases, just as the Moon goes through phases when viewed from Earth. Suppose you were on the Moon at the time Figure 16.15 was taken. What phase was Earth in?

Notice that the shadows in the craters are deepest near the dark half of the Moon. To understand this, ask yourself what time of day on Earth your shadow is longest. Could we use the length of a mountain's shadow to calculate its height? How? (2)

Study Figure 16.16 carefully. Which formed first—the flat areas or the craters? (3)

(2) Yes, by setting up a proportion.

(3) According to the USGS, the oldest features are the mountains and the youngest are the craters. Any student's interpretation is acceptable if it can be defended. This could make a good class discussion.

The environment of the Moon. Some of the things essential for life as we know it are water, food, and air. None of these things have been found on the Moon. Earth is just far enough from the Sun to receive the right amount of energy in the form of sunlight to make Earth's surface favorable to life. The Moon and Earth are about the same distance from the Sun. Then why is the Moon's environment so different from Earth's? The main reason is that the Moon has no protective atmosphere to stop harmful radiation and soften the Sun's influence. The lack of an atmosphere on the Moon is related to the Moon's weak gravitation, as we will discuss later. On Earth, the atmosphere reduces the temperature changes between day and night. And despite this, it is colder at night than during the

Figure 16.17 The object at left is Venus. This photograph was made when the edge of the Moon almost covered Venus.

daytime. But on the Moon, the temperature at night is -156°C, and during the day it is about 100°C. On the Moon's night side, even air would freeze solid; while on the day side, water would boil! Without an atmosphere, there can be no weather on the Moon. This means no rain, no clouds, no winds—just the harsh direct rays of the Sun in a black sky. (Our sky is blue only because of the atmosphere, which scatters sunlight in a way that makes the sky appear blue and prevents us from seeing the stars. On the Moon, the stars are visible during the day.) Without the pressure of an atmosphere, water boils more easily. Even on the Moon's cold side, water (and ice) would quickly evaporate. On the hot side, the absence of pressure and the high temperature would combine to make water disappear even more rapidly. Except for water that might be trapped in rocks or under the ground, all the water on the Moon would have escaped into space long ago. (6)

How did we know all this before we went to the Moon? Figure 16.17 provides a clue. It shows the Moon passing in front of a planet, in this case Venus. Notice how clear and (7) sharp the image of Venus is. If the Moon had an atmosphere,

(6) Added interest might be injected if you requested from NASA photographs showing the environments of all of the different Apollo landing sites and then let your students compare them.

(7) This is called an *occultation.*

what would we expect to happen? (Think of how the Sun shimmers and seems to change shape at sunset seen from Earth. What causes this to happen?) Look at Figure 1.1. Do you see how that picture also demonstrates that the Moon has no atmosphere?

The prospects for a visitor to the Moon are not very encouraging. But man has faced difficulties before in order to explore the unknown. In the past, man has found ways to supply his needs while crossing deserts, climbing high mountains, diving to the ocean depths, and conquering the South Pole. To conquer the Moon, man has traveled in pressurized spacecraft, and on the Moon's surface he has worn bulky space suits. Indeed, he has carried a little piece of Earth's environment with him to the Moon. A space suit not only provides the astronaut with air to breathe, but also keeps the astronaut's body (1) under the right temperature and pressure to function normally.

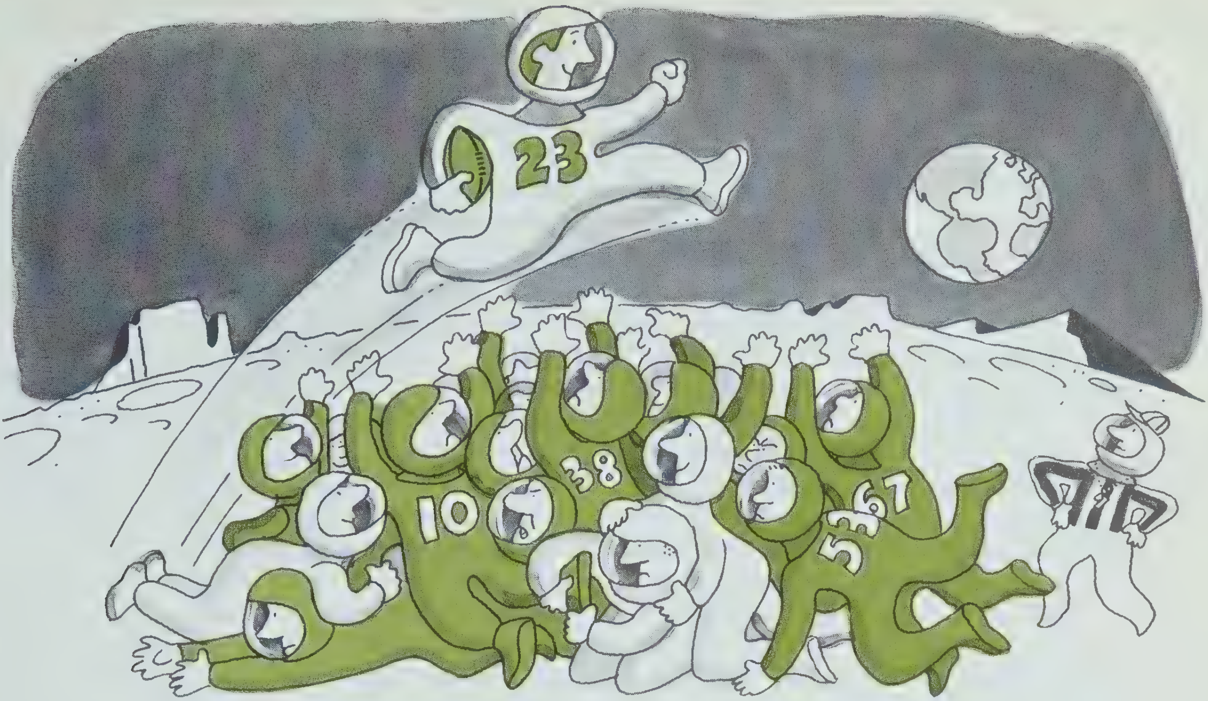
(1) If the pressure suit failed, the astronaut's body would expand, he would bleed, and his blood would boil (vaporize).

Your weight on the Moon. How much would you weigh on the Moon? Although you would still have the same mass, your weight would be only $\frac{1}{6}$ of your weight on Earth. In fact, everything on the Moon would have only $\frac{1}{6}$ of its weight on Earth. Because the Moon's mass is much less than Earth's, the Moon's gravitation is much weaker than Earth's.

But while everything would be much lighter on the Moon, you would still have your normal strength. Could you throw a baseball fast enough to "put it into orbit"? No, but you could throw it much farther than you could on Earth. Athletic events on the Moon would be very different. Many records would be broken. Of course, all the athletes would have to wear space suits. Athletes' endurance would probably be greater because of low gravitation. According to the Apollo astronauts, living, (2) working, and playing in a low-weight environment is quite pleasant in some ways. The astronauts commented that they didn't tire nearly as quickly as on Earth. On the Moon, would a man require more or less sleep, and would his workday be longer or shorter?

(2) Start a discussion by asking what it would be like if Olympic Games were some day held in the Sea of Tranquility.

Astronomy from the Moon. The Moon's weak gravitation explains why it has no atmosphere. A planet's (or a moon's) atmosphere is composed of various gases, and all gasses tend to expand if they are not trapped inside containers. The only "lid" that traps a planet's atmosphere is the gravitational pull of the planet on each molecule and atom in the atmosphere. The larger the planet, the stronger the pull, the better the lid.



The Moon is simply too small to provide a very good lid for an atmosphere. Even if we could donate part of Earth's atmosphere to the Moon, the Moon would soon let it get away.

(3) (3) Perhaps we could build huge "astrodomes" on the Moon.

There are many advantages to studying the universe from the Moon rather than from Earth. Earth's atmosphere is a great nuisance to astronomers. It blocks nearly all the ultraviolet radiation from the Sun and other stars. Even though it lets visible light through, it distorts the path of the light. This is what causes stars to twinkle. The effect is magnified in a telescope. As a result, an astronomer on Earth never has an ideal star image. On the Moon, with no atmosphere to bend and distort light, we will be able to measure the position of stars much more accurately and see finer details in galaxies (large collections of stars). On the Moon, huge telescopes will be easier to handle, because of their reduced weight. It would be impossible, or at least impractical, to build an optical telescope (a telescope that gathers visible light rather than radio waves or other radiation) much bigger than the Hale telescope at Mt. Palomar, California, which is 5.08 meters (200 inches) in diameter. Experts say that an optical telescope 25 meters in diameter could be built on the Moon. With a very large, Moon-based telescope, we could see farther and get information that would help us get some more answers to big questions like "How and when was the universe formed?"

Life on the Moon. Conditions on the Moon are certainly not favorable for life. Yet life takes many forms, and even on Earth, life survives under extremely difficult conditions. So when samples of lunar soil were brought back by Apollo astronauts, a careful search was made for signs of life. Disappointing as it may seem, there is so far not the slightest evidence that there was ever any life on the Moon. In hundreds of separate (1) tests, the results have always been negative.

(1) You might start a discussion by asking your class to describe the appearance and habitat of creatures inhabiting the Moon.

One way to look for signs of life is to look for carbon compounds. Proteins, sugars, and fats—the substances that make (2) up living tissue—all contain carbon. Only a few kinds of carbon compounds have been found on the Moon, and the presence of these compounds can be explained without assuming that life was ever present. Scientists believe that many compounds found on the Moon are the result of the bombardment of the Moon by the solar wind, which consists mostly of protons (hydrogen nuclei) and electrons, but also contains nuclei of heavier elements, such as carbon. One of the compounds that have been found in lunar rocks is the gas methane, CH_4. On Earth this gas is commonly produced by living organisms. On the Moon, however, its presence can be explained as the result of solar wind bombardment.

(2) All the living organisms we know contain carbon, hydrogen, oxygen, and nitrogen.

Scientists searching for signs of life in the lunar material did make one peculiar discovery. When they placed certain plants in the powdered rock brought back from the Moon, the plants grew much faster than when they were growing in ordinary soil from Earth. The plants became greener. Lunar soil is indeed a good fertilizer, but a very expensive one!

Erosion on the Moon. As you have learned, the dominant agents of erosion on Earth are water, wind, ice, and gravity. On the Moon, the first three simply do not exist, and gravity is considerably weaker. Does this mean that weathering, erosion, and the whole rock cycle cannot exist on the Moon? Certainly (3) erosion is a very different process on the Moon than here on Earth, but it does take place. Something must break the Moon rocks into the soil that covers much of the Moon's surface. Moon soil recovered to date is brownish or grey and is composed of fine particles.

(3) Definitely not.

Even without weather, it is possible to explain the origin of the Moon's soil and other features. Certainly mechanical weathering takes place on the Moon. Drastic temperature differences between day and night would cause Moon rocks to alternately expand and contract and eventually crack. The

most important cause of erosion on the Moon, however, is bombardment by particles from space. (Why is this not an important cause of erosion on Earth?) The Moon is constantly **(4)** bombarded—not only by the solar wind, but also by a variety **(5)** of other particles. Most important are the **meteoroids**, which are chunks of rock and metal that travel around the Sun. The very smallest meteoroids are called **micrometeoroids**; they are microscopic in size. The constant rain of these tiny particles "sandblasts" the Moon's surface, chipping away at the Moon rocks. Figure 16.18 shows a microscopic pit in lunar material caused by the impact of a micrometeoroid. Glass beads of microscopic size are often found in lunar dust (Figure 16.19). How do you think these glass beads might have been formed? **(6)**

The particles broken from lunar rocks by bombardment are also very small in size. Over billions of years, they would make up the lunar soil. Gravity would slowly pull the lunar soil down from the mountains and high regions to fill in the craters and the low, flat areas. Scientists calculate that it takes a million years just to wear down a few millimeters of lunar rock.

(4) Because Earth's atmosphere consumes, by friction, most of the particles that come in from space.

(5) Solar wind particles have been found embedded in the bottoms of some Moon rocks. This information suggests that the rocks have been moved.

(6) Scientists think these beads were formed by *impact metamorphism.*

Figure 16.18 (below left) This photograph, taken through a microscope, shows a pit made by the impact of a micrometeoroid.

Figure 16.19 (below right) This photograph, also taken through a microscope, shows the glass beads found in lunar dust. The beads shown are several hundred angstroms in diameter.

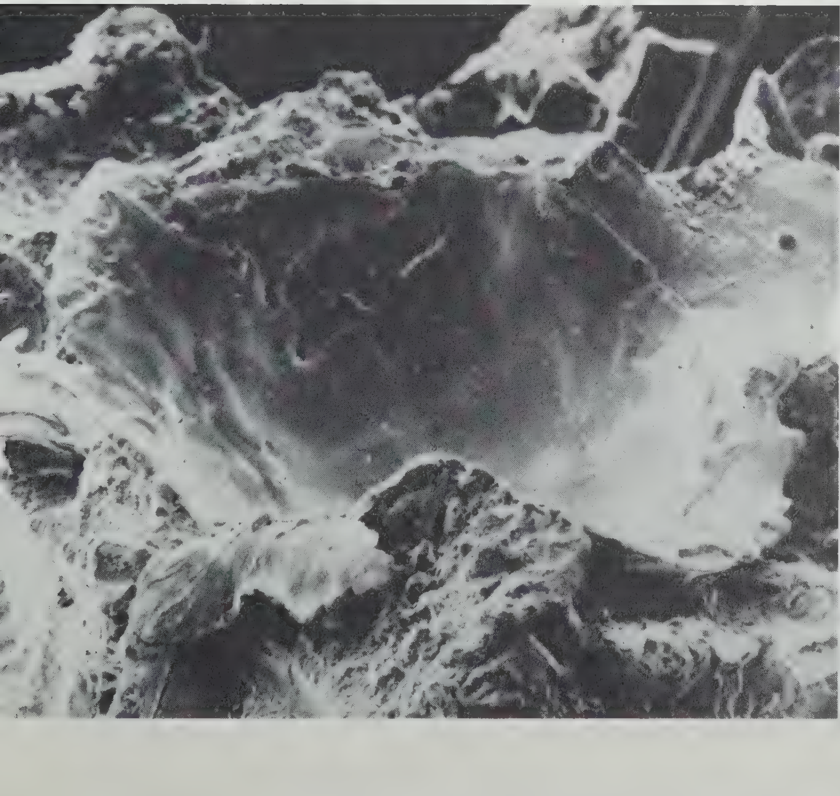


Figure 16.20 The 4.5-kilogram breccia shown at left was brought back in the Apollo 15 mission to the Moon. A microscopic view of a lunar breccia is shown in the photograph at right.

CHECK YOUR FACTS

1. What evidence do we have that the Moon has little or no atmosphere?
2. What would be the advantages of Moon-based telescopes?
3. Have signs of life been found on the Moon?
4. What are some causes of erosion on the Moon?

(1) (1) **ANSWERS** / Check Your Facts

1. Through an occultation of the edge of the Moon against the Sun during an eclipse. Also observations by astronauts.
2. For optical telescopes: clarity of atmosphere and no refraction, as well as increased magnitude resolution. For radio telescopes: no radio, television, and radar interference.
3. Certainly, now—people have been there, but no evidence has been brought back.
4. Micrometeoroid bombardment, extreme variations in temperature, solar wind (electrostatic) bombardment, and gravity.

MOON ROCK AND MOON HISTORY

Kinds of Moon rock. Moon rocks can be divided into three main groups: coarse-grained crystalline rocks, fine-grained crystalline rocks, and **breccias** (Figure 16.20). The coarse- and fine-grained crystalline rocks appear to have an igneous origin. What does the fine texture tell us about the conditions under which the rocks formed? The breccias are composed of angular fragments that appear to be cemented

(2) (2) Fine-textured igneous rocks suggest rapid crystallization, perhaps near the surface.

together. Why aren't the breccia particles rounded? Some of (3) the breccia material shows evidence of having been mixed and then redeposited as impact debris (material scattered by the impact of a meteorite).

The Moon's surface contains many silicate minerals. With (4) these silicates there is an abundance of free iron, which is rarely found in Earth rocks. Moon rocks also have a high concentration of titanium and zirconium, not typical of most Earth rocks. (5)

In addition to microscopic glass spheres, Moon rocks also contain larger, visible glass spheres. Many Moon rocks are covered with these glass spheres, which act like reflectors and give the rocks a glittery appearance. It is believed that when a meteorite hits the Moon's surface, it melts enough rock to make a puddle of molten rock. The impact splashes some of the molten rock into the lunar vacuum, where it immediately cools and solidifies into glass spheres.

Lunar geologists have attempted to discover whether rocks exposed on the Moon's surface had ever been disturbed—for example, by a moonquake or by a meteorite crashing nearby. Evidence shows that at least some Moon rocks were tumbled about on the Moon's surface after they were formed. (6)

Age of Moon rocks. As you know, there is great variation in the age of rocks found on Earth. Do Moon rocks show the same variation? Scientists have performed extensive tests using dating techniques based on the radioactivity of lunar samples. The crystalline rocks are reported to be more than 3.5 billion years old, while samples of the soil and breccias are as much as 4.6 billion years old. The soil samples and breccias may represent some of the original surface material. (7)

The Moon's interior. Exploration of small areas of the Moon's surface by Apollo astronauts has given us much information about the surface. But what is the Moon's interior like? Is it composed of layers like Earth, or is it uniform throughout? An answer is provided by a study of seismic waves. Seismographs have been placed at various places on the Moon. From the seismic studies, it was concluded that the Moon's central core is neither as hot nor as dense as was once believed. It is now believed that the increase of temperature with depth on the Moon is two or three Celsius degrees per kilometer. This suggests that the temperature at the center of the Moon is between 800 and 1000°C. This low temperature, which is

(3) The breccias, by definition, are composed of angular fragments. The fragments would be rounded only if they were eroded by water.

(4) Apollo 16 samples, for example, show an abundance of anorthosite (silicate rock).

(5) Have your class make an exhibit of rocks similar to those found on the Moon. Include fine-grained igneous rocks, coarse-grained igneous rocks, and breccias.

(6) Solar wind particles embedded in the bottom of some rocks.

(7) Refer back to Chapter 9, where radiometric dating is discussed.

only one fifth of the central temperature of Earth, would imply that most of the Moon is solid.

(1) (1) Earth's outer core is thought to be liquid, and seismic waves confirm this conjecture.

Other Apollo devices measured the Moon's magnetic properties. The Moon's magnetic field is a thousand times weaker than the magnetic field of Earth. In fact, it is so small that it is barely detectable. This observation, some scientists feel, confirms that the Moon is solid throughout. Why?

Origin of the Moon. Many of the Moon's features are difficult to explain, but the most difficult question of all is how the Moon itself was formed. No other planet has a moon so large compared to the planet itself. In fact, our Moon is so large compared to Earth that Earth and the Moon together are sometimes called the "double planet." There are several theories of how the Moon was formed. According to one theory, the Moon was once an independent planet traveling around the Sun. It strayed too close and was captured by Earth's gravitation. Another theory is that Earth and the Moon formed at the same time. A whirling cloud of dust condensed into two separate bodies. One body became the Moon and the other became Earth. Today astronomers favor the second theory, but they are by no means sure that it is correct.

(2) (2) Assign class reports on the various theories about the origin of the Moon.

CHECK YOUR FACTS

1. What are the three main groups of Moon rocks?
2. How were the Moon's glass spheres formed?
3. How old are the oldest Moon rocks?
4. How hot is the Moon's interior?
5. What are two theories of the Moon's origin?

(3) (3) **ANSWERS** / Check Your Facts

1. Fine-grained, coarse-grained, and the breccias.
2. The impact splashes cool immediately into glass spheres.
3. As of 1971, 4.6 billion years, older than any known Earth rock.
4. On the basis of the "dead body" theory, the temperature at the center of the Moon is thought to be 800-1000°C.
5. (a) The Moon was an independent planet that strayed too close. (b) Both Earth and the Moon were formed at the same time.

APPLYING WHAT YOU HAVE LEARNED

1. Does the Moon move eastward or westward across the sky? Explain.

2. Would the different distances from Earth to the Moon affect the appearance of a total solar eclipse? Explain.

3. Suppose the Moon and the Earth were nearly the same mass. Where would we find the center of mass of this system?

(4) (4) **ANSWERS** / Applying What You Have Learned

1. Really eastward. The Moon revolves around Earth toward the east, but because of Earth's rotation, the Moon seems to go toward the west.
2. Yes, because it changes the apparent angular diameter of the Moon.
3. Midway between the two bodies.

4. What is the difference between the dark side of the Moon and its hidden side?

5. Are the Moon and the Sun the same size in the sky? Explain.

6. How is it possible to have a high tide on both sides of the Earth at the same time?

7. Would Earth exhibit phase, as the Moon does, if you were on the Moon looking back at Earth?

8. Why does the Moon's temperature change so drastically?

9. How much would you weigh if you were on the Moon?

10. What would you assume if we found solar wind particles embedded on the bottoms of undisturbed lunar rocks?

KEY WORDS

ellipse (p. 311)
gravitational force (p. 311)
quarter moon (p. 314)
full moon (p. 314)
new moon (p. 314)
phase (p. 314)
lunar eclipse (p. 315)
solar eclipse (p. 315)
high tide (p. 316)
low tide (p. 316)
meteroid (p. 325)
micrometeoroid (p. 325)
breccia (p. 326)

4. The hidden side of the Moon (41%) is the part we never see. The dark side is any part of the Moon not receiving sunlight at the time, and may include part of the hidden side.
5. They are approximately the same apparent size, as can be seen during a total eclipse of the Sun.
6. The gravitational pull of the Moon pulls the water on one side of Earth and Earth's crust away from the water on the other side of Earth.
7. Yes.
8. Reradiation occurs rapidly because there is nothing to hold the heat.
9. Answers will vary; all will be approximately 1/6 of the students' weights here on Earth.
10. That they had been moved in some way, possibly by gravity.

Figure 17.1 How do you think these features on Mars might have been formed? (1)

Introductory Demonstration

You will need a bead (drop) of Hg (Mercury), a few crystals of $(NH_4)_2Cr_2O_7$ (ammonium dichromate), some dilute HNO_3 (nitric acid), and a watch glass or petri dish.

Ask your students to compile on the board a list of properties of living things (e.g., growth, respiration, reproduction). While they are doing this, carefully pour the HNO_3 into the watch glass and drop the bead of Hg into the acid. Then add a crystal or two of ammonium dichromate, and let your students watch what happens. Use an overhead projector if one is available; otherwise, let your students come up in groups to observe. This inanimate object will move violently about the watch glass, will appear to respire, ingest, and even reproduce. This demonstration works beautifully and will initiate a lively discussion.

chapter 17

Other Worlds

It was a quiet and lonely Halloween Eve, October 30, 1938. Imagine yourself sitting in your living room that Sunday evening, half listening to the radio and half reading the Sunday funnies. The music on the air was that of Raymond Racquel and his Orchestra. There was an interruption. Then . . . (2)

> Ladies and gentlemen, we interrupt our program of dance music to bring you a special bulletin from the Intercontinental Radio News. At 20 minutes before 8, Central Time, Professor Farrel of the Mount Guinea Observatory, Chicago, Illinois, reports observing several explosions of incandescent gas occurring at regular intervals on the planet Mars. The spectroscope indicates the gas to be hydrogen, and moving toward the Earth with enormous velocity. Professor Pearson of the observatory at Princeton confirms Farrel's observations, and describes the phenomenon as, quote, like a jet of blue flame shot from a gun, end quote. We now return you to the music of Raymond Racquel and his Orchestra.

(1) They look very much like features formed on Earth by water.

(2) This was part of Orson Welles' portrayal of H. G. Wells' story, "War of the Worlds," ▪ Mercury Theater of the Air Production. Assign a student to report on this event.

This was the beginning of a frightening event, a dramatic interpretation of H. G. Wells' story *War of the Worlds*. It was a broadcast that panicked a nation. It told of invading Martians who blasted off from their planet and landed on a small farm near Grovers Mills, New Jersey. The invaders immediately began to kill people. They disrupted communications, defeated our army, and occupied whole sections of our country. It was a thrilling drama that fooled many listeners. For them, the end of the world had come.

Just how ridiculous is it to suspect that we might someday (1) be visited by beings from a distant planet? Why should we (2) think that we are alone in space? Figure 17.2 shows just a small portion of the sky. Of the billions upon billions of stars in the sky, many must have planets, and some of these planets must have the right conditions to support life.

Life as we know it here on Earth is based on complex chemical reactions involving mostly carbon, hydrogen, oxygen, and nitrogen. To sustain life requires water, food, air, and moderate temperatures. Perhaps these conditions exist elsewhere and perhaps elsewhere someone is asking the same question we are asking: Are we alone? (3)

(1) This may be a good place to discuss UFOs and flying saucers—a real "grabber" for student discussions.

(2) Useful references here are *The UFO Experience,* by J. Allen Hynek (Henry Regnery, Chicago, 1972), *The Anatomy of a Phenomenon,* by Jacques Vallée (Ace Books, New York), and the Condon Committee's UFO report.

(3) Your students may enjoy reading *We Are Not Alone,* by Walter Sullivan (McGraw-Hill, New York, 1966; paperback, New American Library, 1966).

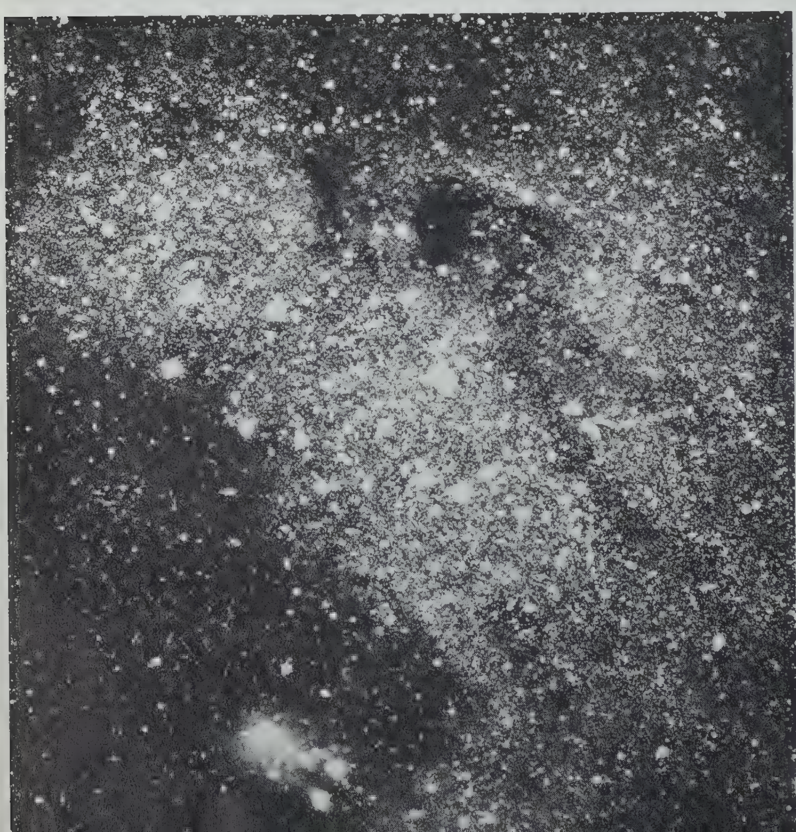


Figure 17.2 Through a telescope, even a small portion of the sky shows many, many stars.

A SEARCH FOR LIFE

The search for life beyond Earth is without doubt one of the most exciting pursuits in the history of mankind. The search for life on the planets of our own solar system has begun, but it will probably be centuries before we can search for life among the stars. The best we can do today is to speculate on the possibility of life elsewhere and to make intelligent guesses. To simplify the problem, it is best to apply the **principle of uniformity** to the structure of the universe. This means that we assume that the laws of science and the basic nature of matter are the same on the most distant stars as on Earth. (In a sense, this principle is an extension of the principle of uniformitarianism from Earth to the whole universe.) If we didn't make this assumption, we would have no place to begin our thinking. How could you think intelligently about a subject if you were completely ignorant about it and could make no assumptions at all about it? (4)

Man has discovered a set of ingredients, called chemical elements, from which all things are made. There are definite rules or principles about how the elements combine to form molecules and how molecules combine to form matter, including living tissues. To eliminate unlikely possibilities and wild thinking from our investigations, we will assume that the chemical elements and the rules governing them are the same throughout the universe. Only then can we begin an intelligent investigation into the possibility of life beyond Earth.

Other stars and planets. The stars are like beacons of light peering from every direction. How many stars are there? And how many of them could have planets that may (5)
have life? To answer these questions with our present knowl- (6)
edge is impossible, but it is possible to make rough estimates.

Some scientists believe that our galaxy, the Milky Way system, contains at least 10^{11} (that is, 100,000,000,000) stars. Pretty big number, isn't it? How long would it take you to count that far? If you counted one star every second of your (7)
life, it would take fifty times the length of your life to count that far.

In the introduction to this chapter we raised the question about whether there might be life elsewhere in space. Let's pursue that question by doing a little arithmetic. Since we are going to have to make many assumptions, don't take any statement in this discussion as a proven fact. Let's start by

(4) Start a discussion about the difficulty of reasoning about things antagonistic toward the uniformity principle. Questions like this: Can you imagine life based on silicon rather than carbon? Obviously you will find this difficult, but the discussion may be rewarding.

(5) Any reasonable answer will do—no one really knows. Perhaps as many as all the drops of H_2O in all the oceans.

(6) Ask questions such as: Do you think it is the exception rather than the rule that stars have planets?

(7) Counting at the rate of one star per second, it would take 33 years of continuous counting to reach 1 billion.

assuming that approximately one out of ten stars in our galaxy is like our Sun. One tenth of 10^{11} is 10^{10}. (Work this out to prove to yourself that it is so.) Thus, there might be 10^{10} stars that are like the Sun. The distance Earth is from the Sun has a great deal to do with life on Earth. (Earth is within the "life zone"—not too close to the Sun and not too far away.) So perhaps we need to look for a planet that revolves around a Sun-like star, at a distance about equal to the Sun–Earth distance, **(2)** give or take a few million kilometers. Of all the stars like the Sun, let us say that one out of ten have planets around them. This gives us 10^9 stars with planets around them. Of those, it **(3)** would not be unreasonable to say that one out of ten may have a planet in the life zone. This gives us 10^8 planets in the life zone. Of those planets, how many have something in common with Earth? One out of ten again wouldn't be unreasonable—giving us 10^7. How many of those planets could possibly have the requirements to sustain life of some kind? Let's say only one out of 100. This leaves 10^5 planets that could contain some form of life. Of those, how many could contain forms of life that we would call "intelligent"? Perhaps 10^4? Or 10^3? Very hard to say.

Remember, we have been talking only about our galaxy. Although our galaxy is unimaginably huge, it is but a tiny speck in the universe. So let's not think that, in the whole **(4)** universe, we're the only intelligent beings!

Now that you are fairly well convinced that life may exist on some remote planet about some distant star, let's take an imaginary trip to such a planet.

A trip to the stars. At present, our speed in space is limited to about 40,000 kilometers per hour. At this rate, how long would it take to travel to another solar system? Say to a close one—only 40 trillion kilometers away. Perhaps before **(5)** thinking about a trip like this you should investigate the distances to the stars and even to the galaxies. How far is the nearest star and how long would it take to travel there?

First let's consider **Proxima Centauri**, the star nearest us other than the Sun. Proxima Centauri is 270,000 times farther from us than the Sun is. Even if we could travel at the speed of light (300,000 kilometers per *second*), a trip like this would take over four years. At 40,000 kilometers per hour, would you live long enough to make the journey? Figure it out. (The Sun is about 150 million kilometers from us.)

Suppose you could travel 40,000 kilometers per *minute*, how long is the trip? How about 40,000 kilometers per *second*?

(2) One Earth-Sun distance is about 150,000,000 kilometers; it is called an astronomical unit.

(3) This would be a good place to review scientific notation (exponents).

(4) It has been said that there may be 5,000,000,000,000 (5.0×10^{12}) galaxies in the universe.

(5) The idea here is not to arrive at a correct answer but simply to realize that it would take a long, long time.

"LIFE, YES- BUT AS FOR INTELLIGENT LIFE, I HAVE MY DOUBTS."

Maybe now you begin to realize that a trip to the nearest star (and to a planet that *might* be orbiting around it) would take a long time! And, unluckily, scientists suspect that (7) Proxima Centauri does not have a planetary system. So our journey to a possible candidate becomes even longer. Before such an immense undertaking, we ought to examine some evidence that other planets beyond the Sun really do exist.

(7) This star is not seen from most places in North America as it lies only 30° from the South Celestial Pole.

We learned in the last chapter that as the Moon revolves around Earth, Earth must move as well. The two really revolve together about a balance point between them. The same is true for a planet revolving around a star. If the planet is large enough compared to the star, it will cause the star to slightly shift its position back and forth. This effect is commonly observed in double stars. (A double star is a pair of stars that revolve around each other.) But some stars that "wiggle" like this have no star close to them. Astronomers believe that this motion is due to an unseen planet revolving around the star. In some cases they have even calculated the mass of the planet.

OUR FAMILY OF WORLDS

Let us now look closer to home—at the planets of our solar system. On a clear night, you can almost always see one or two planets in the sky. Including Earth, there are nine planets in the system. How big are the planets and how far away are they (1) from the Sun and from Earth? Activities 17.1 and 17.2 will (2) help you answer these questions.

(1) Recently there has been some spectroscopic evidence to suggest a tenth planet beyond the orbit of Pluto.

(2) Refer to Activity 17.1.

(3) See Commentary, page T19.

activity 17.1 *Solar system sizes*

The table below gives the diameters of the Sun, planets, major asteroids (small bodies orbiting around the Sun), and natural satellites of the solar system. Imagine that you are given the items in the first column and that you are making a model of the solar system with them. Match up each of the items with the part of the solar system it represents. (3)

		Diameter (kilometers)
a red apple	Sun	1,392,000
a 15-meter (50-foot) ball	Mercury	4,840
a handful of birdseed	Venus	12,200
an orange	Earth	12,742
a 1.5-meter (5-foot) ball	Mars	6,720
a soft ball	Asteroids	up to 770
a handful of plums	Jupiter	138,000
a 1.7-meter (4 feet and 2 inches) ball	Saturn	115,000
a lemon	Uranus	48,000
a bunch of grapes	Neptune	45,000
2 beach balls	Pluto	5,800 ?
a grapefruit	32 satellites	up to 5,000

activity 17.2 *Solar system distances*

You now have an idea of the relative sizes of the members of the solar system. But what about the distances between them? To get an idea of the relative distances, let's put the solar system on your football field.

If the length of your football field represents the radius of the solar system (that is, if the Sun is on one goal line and Pluto is on the other goal line), where would the other planets and the asteroids be? In the following table, the distance of the planets and asteroids from the Sun is given in *astronomical units.* One astronomical unit, or AU, is the average distance of Earth from the Sun (about 150 million kilometers). Go out to your football field and mark the places where the planets and asteroids would be. (4)

Planets	Distance from Sun (AU)
Mercury	0.4
Venus	0.7
Earth	1.0
Mars	1.5
asteroids	2.8
Jupiter	5.2
Saturn	9.5
Uranus	19.2
Neptune	30.1
Pluto	39.5

(4) See Commentary, page T20.

(5) Mercury has a small elongation angle (It doesn't get far enough away from either side of the sun.), and so remains near the horizon. We see it then through a thicker layer of our atmosphere.

(6) Until a few years ago it was thought that Mercury's rotation period equalled its revolution period. This is *not* true. Mercury rotates in 59 days and revolves in 88 days.

(7) Most experts think that Mercury is covered by craters just as is our Moon.

(8) Hardly! They are too extreme.

A look at the Mercurian world. A good place to begin our study of the planets is the planet Mercury. Twinkle, twinkle, little planet! Perhaps you have heard that one way to tell a planet from a star is to see if it twinkles. Stars twinkle; planets don't. But there is one planet that does: Mercury. Mercury is usually too close to the Sun to be seen. During the few days a year when it is visible, it is near the horizon and is difficult to observe. Can you think of a reason why it twinkles (5)
so much?

Mercury is indeed hot. Lying so close to the Sun, it really feels the Sun's fiery breath. Surface temperatures on Mercury probably rise above 350°C during the day and drop below −180°C at night. Knowing these things, do you think Mercury (6)
has an atmosphere? Is it reasonable to expect that Mercury's surface is covered by many pits and craters? Do you think life (7)
as we know it could exist in such an environment? (8)

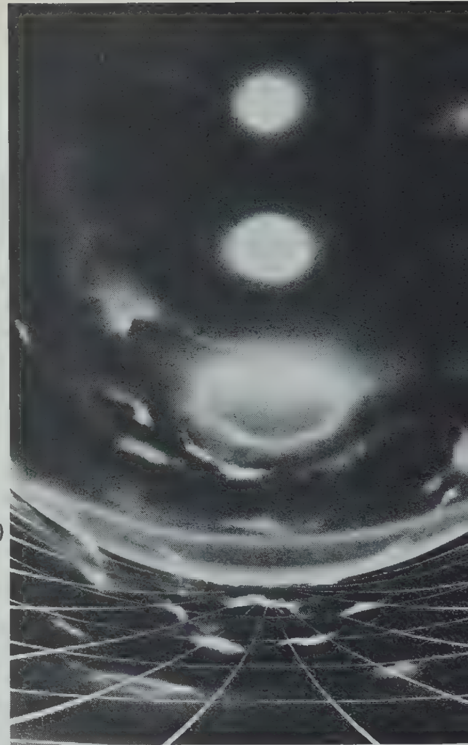
The world of Venus, goddess of love. Rotating ridiculously backward, the planet Venus is (at times) our nearest neighbor beyond the Moon. In size, Venus is nearly Earth's twin. In distance it is only one third closer to the Sun than is

Earth. Its mass is also close to that of Earth. Since there are so many similarities between the two planets, wouldn't you think other conditions might be similar too?

Venus's axis of rotation is perpendicular to the plane of its orbit–not tilted like Earth's axis. What would the seasons be like on Venus? Would there be summer and winter? If you lived on Venus's north or south pole, would the Sun appear high in your sky or would it always be on your horizon?

Various space probes have shown that the temperature on the surface of Venus gets above 400°C, hot enough to melt lead. The atmosphere of Venus is 95 percent carbon dioxide. Do you think this has something to do with the high temperatures on Venus? (Remember the "greenhouse effect" from (4) Chapter 13?) Figure 17.3 shows an artist's imaginary view of a sunset on Venus.

Most scientists now believe that because of the extreme temperature of Venus, life as we know it simply could not exist there. There are certain microorganisms on Earth that can live in hot springs at very high temperatures—but not at anything near 400°C. It seems that "Venus," Roman goddess of love, is a wrong name for this planet!



(5) **Figure 17.3** This imaginary drawing shows various stages of a sunset on Venus. Because of the extreme refraction (bending) of light by Venus's atmosphere, everything on Venus appears distorted. As the Sun touches the horizon, it spreads into a band of light along the horizon. No one knows yet whether Venus's atmosphere is transparent, as shown here. It may be not transparent at all, or only slightly transparent.

The world of Mars, god of war. Over fifty years ago a wealthy French woman offered a large reward for anyone who could communicate with someone on some other planet. She made, however, one exception—Mars. "Everyone suspects Mars to have life," she explained.

Many astronomers believed that they saw long, straight lines on the Martian surface when they studied Mars through a telescope. Percival Lowell, a famous astronomer of the early 20th century, believed Mars was the home of highly civilized beings and that the lines on the Martian surface were canals that formed a complex irrigation system. The Martian centers of population were located in the oasis where the canals crossed. (An oasis is a well-watered spot with much vegetation.) The use of the term "canal" for the lines of Mars came about through a misunderstanding. An Italian astronomer, Giovanni Schiaparelli, had called the lines "canali," the Italian word for "channels." Eager beavers translated the word into "canals."

In 1894 Lowell wrote, "Certainly what we see hints at the existence of beings who are in advance of, not behind us in the journey of life."

In recent years, the Mariner space probes have radioed back many photographs of Mars. None of the photographs

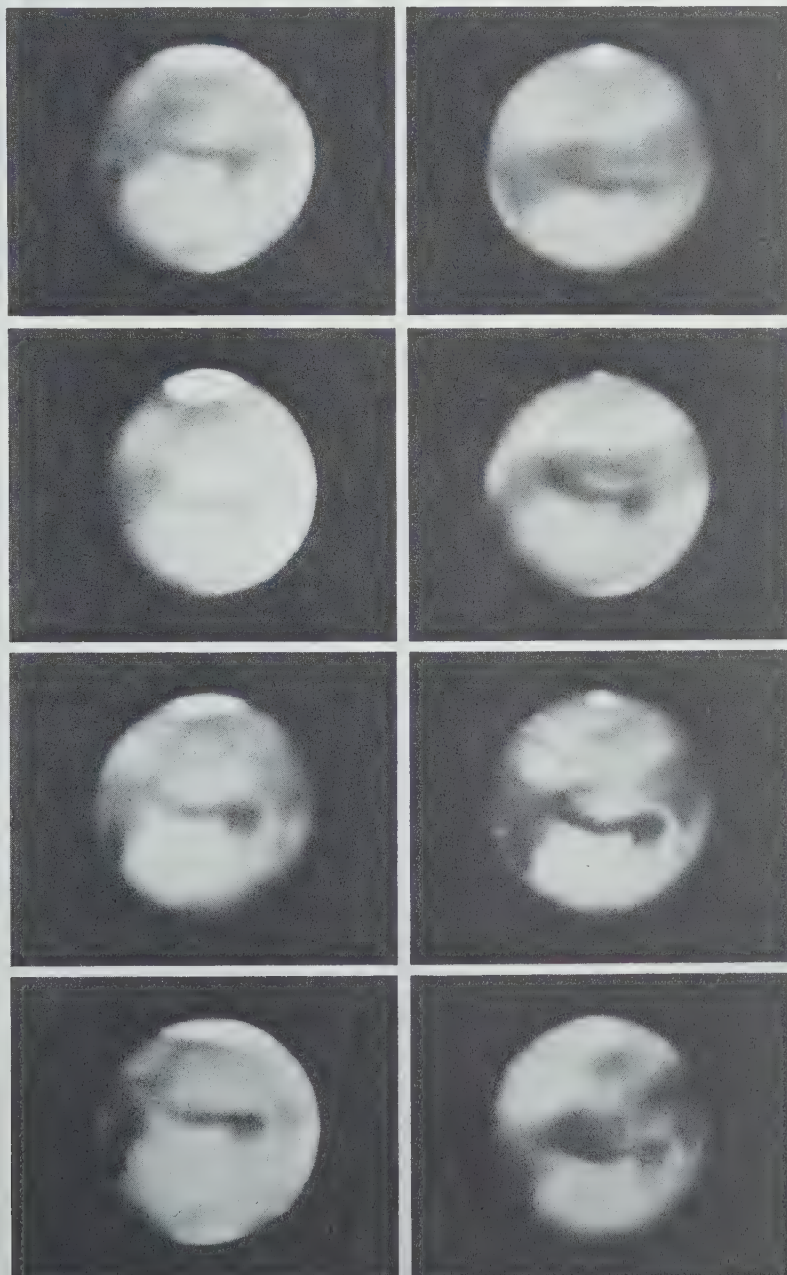
Figure 17.4 (right) These photographs, taken at different times, show the changing face of Mars.

(4) Carbon dioxide is a pollutant. It is also a good insulator and would tend to hold the heat in.

(5) Have your students prepare a report on the information gathered from the Mariner probes to Venus.

Seasonal Development Of The Dark Markings

Spring Summer



Apr. 17, 1907 June 29, 1909

May 11, 1924 Aug. 1, 1926

May 2, 1939 July 11, 1941

Mar. 15, 1954 June 7, 1956

(1) Put on display a large color photograph of the planet Mars.

shows any lines or canals! What do you think Schiaparelli really saw when he described his "canali"? Were they only in his imagination?

Perhaps your teacher has a large photograph or sketch (1) of Mars (without the canals). Request that each student in your class be allowed to draw what he sees from where he is (2) seated in the room. Discuss what each student sketched. (3)

Figure 17.4 shows various photographs of Mars taken through a telescope on Earth. Hold the book at arm's length and squint at the photographs. You might be able to imagine that you are seeing lines on Mars's surface. The early astronomers who thought they saw lines on Mars's surface did not have telescopes as good as the one used to take these photographs. Their view of Mars was even fuzzier than these views. If they could have seen more clearly, their imaginations might not have run so wild!

Today we have crystal-clear pictures of the Martian surface taken by various Mariner spacecraft as they passed by (4) Mars or as they orbited around it. Figure 17.1 is a Mariner photograph covering about 1000 square kilometers of the Martian surface. Do you see any canals? What feature other (5) than the craters do you notice? Does this feature look like a (6) canal or does it look like a natural feature? What feature on (7) Earth does it resemble? (8)

Figure 17.5 (above) This mountain on Mars is bigger than any mountain on Earth. How do you think this mountain formed? **(11)**

An observation supporting the idea that there is at least plant life on Mars is the apparent change of colors seen on the surface during the different seasons. Parts of the surface appear to turn rusty brown in the autumn and green in the spring, suggesting that the planet might have vegetation. It was once thought that the dark areas might be forests like those on Earth. (9)

Mariner photographs show no presence of vegetation on Mars. They do show, however, that gigantic dust storms take place on Mars. These dust storms change some surface features of Mars and may have something to do with the seasonal color changes. (10)

The space scientist Robert Leighton suggests that the reddish color is due to ultraviolet radiation hitting carbon trioxide (C_2O_3). Under the influence of the radiation, the carbon trioxide molecules would join together in long chains that would give the Martian atmosphere a reddish color. In the laboratory this experiment produces a strong odor. Dr. Leighton says that "the environment of Mars probably smells like fermented sweat socks."

When man sets foot on the surface of Mars he will feel more normal than he did on the Moon, since the surface gravity

(2) Write NASA for information on the Mariner flights to Mars.

of Mars is one third of that on Earth, or twice as strong as on the Moon.

Since Mars is about 1.5 times farther from the Sun than Earth is, what would you predict the temperature to be on the surface? At noon on the Martian equator it is thought the temperatures can reach 20°C (70°F), a comfortable temperature for us. However, at midnight the temperature drops to below −70°C. Can life as we know it survive such cold? We don't know.

What are the surface features of Mars? Recent studies indicate that mountains on Mars may be higher than Mt. Everest here on Earth (Figure 17.5). By putting many Mariner photographs together, scientists have produced a "world map" of Mars (Figure 17.6). Is the Martian world more like Earth or more like the Moon? (12)

Mars does resemble Earth in some ways. For example, it has an atmosphere. However, the Martian atmosphere has a

(12) Begin a class discussion on this question.

(3) Discussion should emphasize that the detail is not good; therefore some students imagine detail, others don't. It depends on the distance of observation.

(4) Assign a student report on the NASA Viking project—a soft landing on Mars.

(5) No.

(6) A long, meandering "river" with many tributaries.

(7) A natural feature.

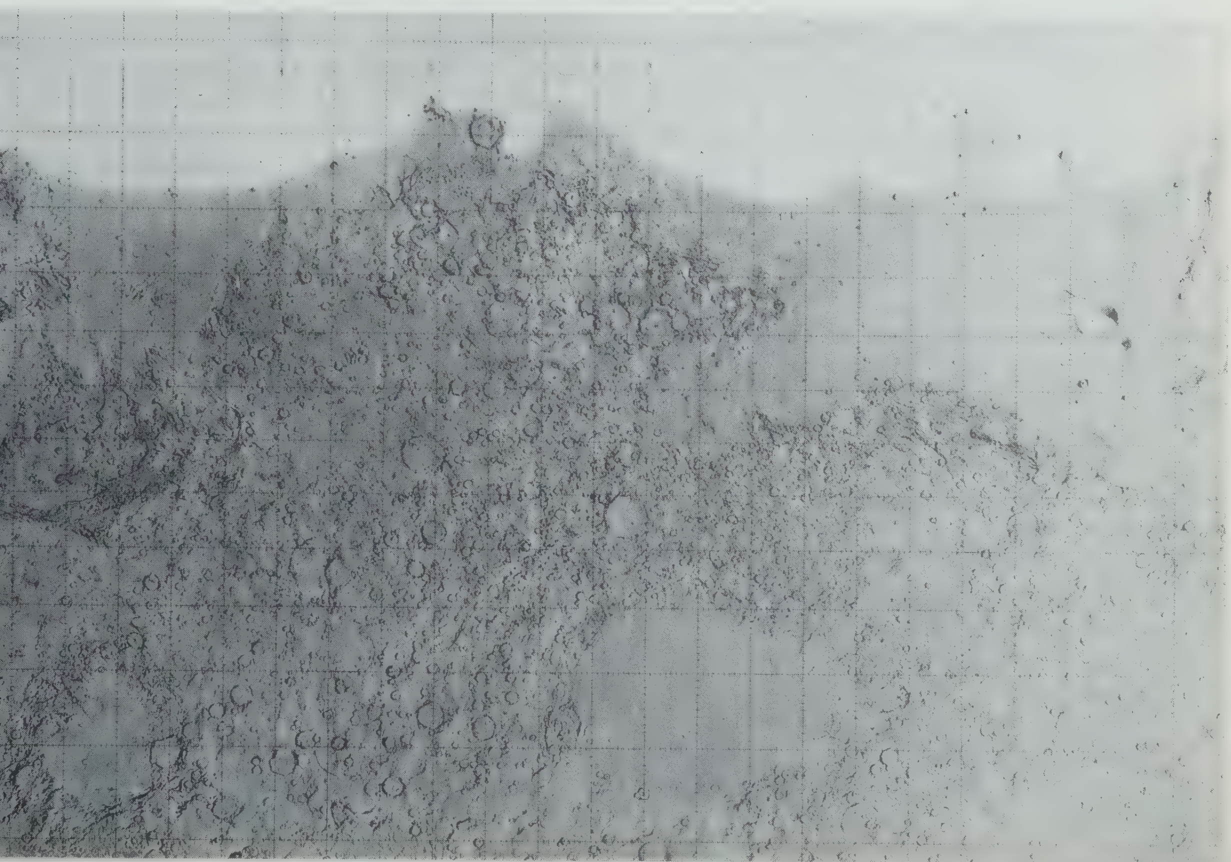
(8) A river system.

(9) To date, there is no evidence that there is life on Mars.

(10) The dust storms confirm that Mars has an atmosphere.

(11) It is a volcano.

Figure 17.6 (below) This map shows all of the surface of Mars except the polar regions. The biggest bump at the left of the map is the mountain shown in Figure 17.5.



very different composition from ours. It is composed chiefly of carbon dioxide; there is some water vapor, but free oxygen is rare. The atmospheric pressure is very low—about what we would find on Earth at an altitude of 30 kilometers. (1)

Laboratory experiments on Earth show that some organisms can grow under conditions that we think are similar to those on the surface of Mars. Some scientists believe that Earth's early atmosphere started out being rich in carbon dioxide. Thus it is possible that Mars's atmosphere has simply not evolved as far as Earth's. If living organisms are found on Mars, what would this mean for man? Under favorable conditions, scientists may develop techniques for transporting man to Mars and possibly altering the Martian atmosphere to make it capable of supporting human life.

Suppose that somehow man made the environment of Mars suitable for you to live in. What would it be like? Would the sky be blue and clear, or would it be cloudy and dark? Because the Martian atmosphere is thinner than Earth's, would you expect the sky to be lighter or darker blue? Even during the Martian daylight hours, the brighter stars could be seen. Imagine stars like sparkling sequins against a background of blue velvet. It would indeed be beautiful.

How do you think our Moon would appear from Mars? Of course its surface features couldn't be visible from a distance of, say, 100 million kilometers without the use of a telescope. But even to the unaided eyes, the Earth–Moon system would look like a bright double star.

Mars has two satellites of its own. According to Roman mythology, Mars, the god of war, had two servants—Phobos and Deimos, meaning "fear" and "terror." So when Professor Asaph Hall in 1877 first observed the two tiny satellites of Mars, it seemed logical to name them Phobos and Deimos. Unlike Deimos, Phobos rises in the west and sets in the east. Phobos is shaped like a baked potato (Figure 17.7) and is 23 kilometers long and 18 kilometers wide. Deimos is smaller. We have also found out that Mars's satellites follow nearly circular orbits—Phobos at about 6,000 kilometers up and Deimos some 20,000 kilometers up. Because they are so close to Mars, what do you suppose the future holds for these satellites? Some scientists think that Phobos will slam to the surface in less than 10 million years. Would you expect Deimos to stay in orbit for a longer or shorter time than Phobos? (2)

Where did these satellites come from? According to one Mariner project scientist, the odd shape of these satellites

(1) Ask your class if they could breathe freely at an altitude of 30 km? (Obviously, they could not.)

(2) Not enough facts are given here to answer this question. If Deimos's orbit is degenerating at the same rate as Phobos's orbit, then Deimos could be expected to stay in orbit longer.

Figure 17.7 Phobos, Mars's baked potato.

suggests that they were captured by the planet years ago. A Russian astronomer proposed a rather fantastic idea—the satellites of Mars are artificial! He said that Phobos and Deimos were manufactured by highly civilized beings who inhabited Mars perhaps several millions of years ago. Because various gases escaped from the atmosphere, the inhabitants were forced to launch satellites into space and live in them. Could it be that these satellites are hollow?

Do you think it would be easier to launch a satellite from Mars or from Earth? Some have asked why the satellites of Mars were not seen in 1862 when Mars was closer to Earth and viewed by a larger telescope than the one Professor Hall used when he discovered them in 1877. Could it have been that these were launched into orbit between 1862 and 1877? (4)

It is difficult to think about the type of life that could live on Mars. With little oxygen, extreme variations in temperatures, and a poor supply of water, the size of Martian creatures, if they do exist, perhaps would be very small. An American astronomer has said, "A flea would not stumble over them!" The probability is against finding complex organisms on Mars. To make matters worse, Mars has no ozone in its air, so there would be essentially nothing to filter out deadly ultraviolet radiation. However, here on Earth there are simple microorganisms that can live in an oxygen-lacking environment and are strong enough to withstand exposure to ultraviolet radiation. On Earth a kind of common soil bacterium has thrived in a simulated Martian atmosphere composed chiefly of carbon dioxide. It has withstood the extremes of Martian conditions.

There is a real danger that Earth's microorganisms, transported by a space vehicle, could contaminate the Martian surface. We must thoroughly sterilize any spacecraft that we intend to land on Mars. Also think of what could happen if microorganisms from Mars were allowed entrance to Earth's environment! (5)

Jupiter—a world or a star? To investigate the planet Jupiter (Figure 17.8) requires some serious thought, too. How could a planet 318 times more massive than Earth support life? Can a body more than five times farther from the Sun receive enough energy? Recent studies tell us that Jupiter—a (6) "solar system" in itself with a dozen satellites—is actually putting out 2.5 times the energy that it receives. This suggests that it acts as a tiny star whose furnace never really got going. How can a planet having an atmosphere chiefly of hydrogen,

(4) Sullivan's book, *We Are Not Alone*, has some interesting reading on this subject.

(5) In H. G. Wells' fictional story, "War of the Worlds" something like this did happen. Martian creatures couldn't cope with the microorganisms of Earth's environment.

(6) Begin a class discussion based on these introductory questions.

Figure 17:8 Jupiter, the giant of our planetary system.

helium, methane, and ammonia support life as we know it? Although Jupiter appears to contain a poisonous atmosphere, some scientists think that Earth's early environment was similar.

Experiments in the laboratory (Figure 17.9) show that electrical discharges (like lightning) in a mixture of gases similar to the atmosphere of Jupiter will produce the molecules that are building blocks of simple forms of life. Is it then possible that the atmosphere of Jupiter could offer a natural laboratory to study the origin of life? (1) Jupiter could be teeming (2) with forms of early life resembling those on Earth billions of years ago.

It is thought by some scientists that Jupiter's thick atmosphere also produces a greenhouse effect, trapping not only the Sun's radiation but also the energy the planet itself emits. The surface environment could be as high as a comfortable 20°C, despite Jupiter's great distance from the Sun. Can you imagine Jupiter having warm seas of ammonia rather than water?

Beyond the life zone. As we move out farther into the (3) solar system to Saturn, Uranus, Neptune, and Pluto, the prospect of finding suitable environments for life gets smaller and smaller. Without an abundant supply of solar energy, life as we know it cannot survive. As a matter of fact, to date there is

(1) Refer to the famous Miller experiment. (See any good biology text for this.)

(2) Have your students report on the research done by Dr. Cyril Ponnamperuna of the University of Maryland.

(3) Refer your class to a reference book showing the statistics of the outer three planets. [A good one is *Exploration of the Universe*, by George Abell (Holt, New York, 1969).]

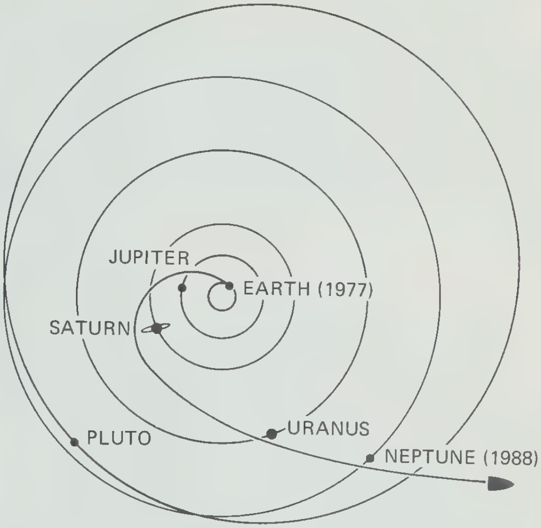


Figure 17.9 (above left) Dr. Cyril Ponnamperuma is one of the leading researchers involved with the possibility of life on planets other than Earth.

Figure 17.10 (above) Scientists hope that "grand tours" by unmanned spacecraft will be started in the late 1970s. This diagram shows one of the proposed tours.

no clear evidence that life exists anywhere in the solar system except on Earth!

Closer investigations of the outer planets will take place in the late 1970s in "planetary grand tour" programs (Figure 17.10). Under the proposed plan, a spacecraft leaving Earth would pass Jupiter and be hurled by Jupiter's gravitational field toward Saturn, and then on toward Uranus, Neptune, and Pluto. Other spacecraft will take tours to Venus and Mercury. These missions will take pictures and measure temperatures, pressures, and magnetic fields. They will also investigate the properties of the planets' atmospheres and, in the case of Mars and Jupiter, look for evidence of life.

CHECK YOUR FACTS

1. What is the principle of uniformity?
2. What is the speed of light?
3. What are some characteristics of Venus's atmosphere?
4. Have Mariner photographs of Mars shown the presence of canals or vegetation?
5. Are there mountains on Mars?

ANSWERS / Check Your Facts

1. The principle of uniformity states that in studying the universe we have to assume that the laws of science and the basic nature of matter are the same in the most distant parts of the universe as on Earth.
2. 300,000 km/sec.
3. The atmosphere of Venus is 95% carbon dioxide. The greenhouse effect produces very high temperatures. The surface temperature gets above 400°C.
4. No.
5. Yes.

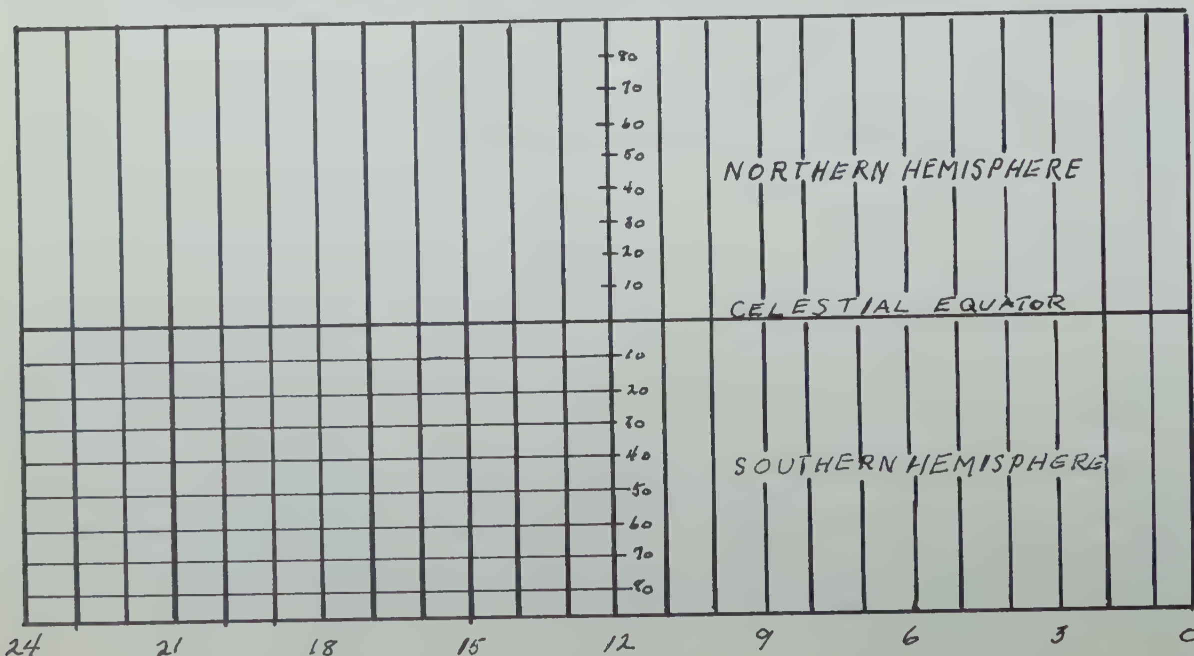
OTHER WORLDS SEEN FROM EARTH

Most of us will probably never have an opportunity to visit the Moon or the planets. However, these other worlds are interesting even if we can only study them from Earth. For example, let's see how Mars moves through the sky when seen from Earth.

activity 17.3 *Plotting Mars's path through the sky*

If your view was not blocked by the horizon, the sky would appear to you like a sphere viewed from the inside. Therefore, making a chart of the sky on a flat piece of paper is like making a flat map of the round Earth. We will use a rectangular piece of graph paper to represent the entire sky, or *celestial sphere*, as it is called. In order to plot the movements of Mars, we must establish a system of coordinates that represents the positions of the fixed stars. Draw a straight line across the middle of a large sheet of graph paper. This line represents the projection of Earth's equator on the sky. It is called the *celestial equator* (Figure 17.11). West is to the right and east is to the left. Above

Figure 17.11 Draw your own chart of the sky, like this one.



the line is the northern hemisphere of the sky; below the line, the southern hemisphere. Since the celestial equator is really a circle, the points on the extreme left and extreme right correspond to the same position in the sky. Because any point in the sky appears to move around Earth in 24 hours, the celestial equator is divided into 24 equal intervals, each interval representing one hour. They are numbered right to left, from 0 hour all the way around to 24 hours, which is the same position as 0 hour. The horizontal position of Mars along the celestial equator is given in hours and minutes (remember there are 60 minutes in an hour); its vertical position north or south of the equator is given in degrees.

From the data given below, plot the position of Mars for the entire year. Connect the points with a smooth line. Does Mars change direction as well as position during the year?

(1)(1) Activity 17.3 plotting Mars' path through the sky. The completed graph showing the looping for Mars is on page T20 of the Commentary.

Positions of Mars, 1971

Month	Horizontal position	Vertical position
January	15 hr 31 min	18°19′ south
February	16 hr 52 min	22°10′ south
March	18 hr 07 min	23°32′ south
April	19 hr 26 min	22°50′ south
May	20 hr 34 min	20°47′ south
June	21 hr 26 min	18°57′ south
July	21 hr 45 min	19°39′ south
August	21 hr 22 min	22°37′ south
September	21 hr 05 min	22°18′ south
October	21 hr 32 min	18°06′ south
November	22 hr 28 min	11°24′ south
December	23 hr 24 min	03°31′ south

(2)(2) The horizontal positions are technically called right ascension and the vertical positions are called declination.

Why is Mars's path so complicated? Why does Mars seem to do loops? Actually, Mars moves in a very simple, almost circular orbit around the Sun. Most of the complications arise because our observing platform, Earth, is moving around the Sun while we are observing the planet. It is the combination of Mars's motion around the Sun and our own motion that causes most of the complexity. Figure 17.12 represents the actual orbits of Earth and Mars around the Sun. When Earth is at E_1, Mars is at M_1; when Earth has moved to E_2, Mars has moved to M_2, and so on. After position E_{12}, Earth returns to E_1, which now becomes E_{13}; E_2 becomes E_{14}; all the previous numbers of Earth's positions are increased by 12. The second time

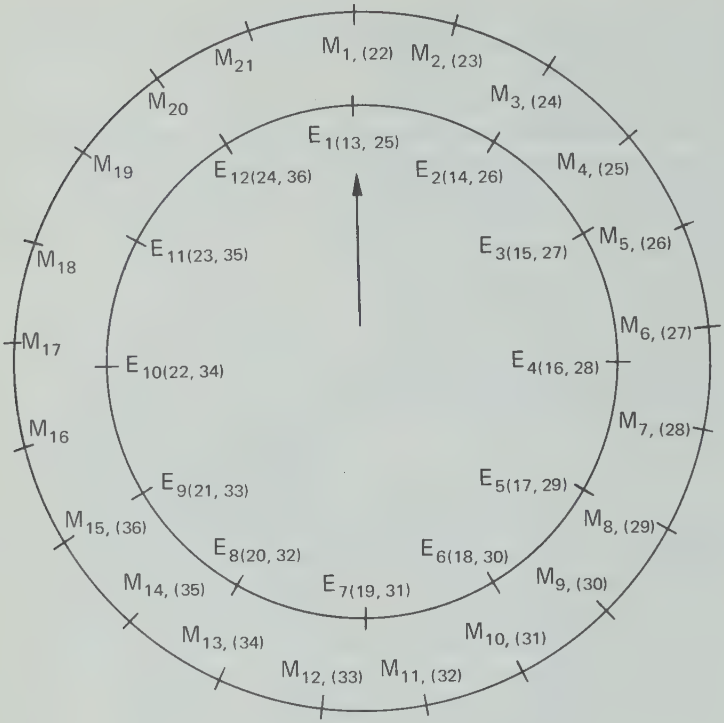


Figure 17.12 Positions of Earth and Mars.

Earth completes its orbit, E_1 becomes E_{25}, E_2 becomes E_{26}, and so on. After Mars has completed *one* orbit, M_1 becomes M_{22}; M_2 becomes M_{23}; all the Mars position numbers are increased by 21.

activity 17.4 *Why does Mars do loops?*

From Figure 17.12 we can plot the path that Mars seems to follow in the sky. The arrow in Figure 17.12 is very important. It represents the direction of a star that we are going to use as our reference point. (1)

(1) See Commentary, page T20.

Place a sheet of tracing paper over Figure 17.12. Trace the arrow that points to the fixed star, draw a circle around the E_1 position, and put a dot on the tracing paper over M_1. Label the dot "1." Keeping the traced arrow parallel to the arrow, move the tracing paper so that the circle is now over E_2; put a dot at M_2 and label this dot "2." Continue moving the circle over all the "E" positions, putting a dot over the "M" position with the

same number, and labelling the dot according to the number of the position. To get a complete pattern, you will have to go around Earth's orbit about 2 1/2 times; meanwhile, Mars will have completed a little more than one orbit. About 30 dots should be enough. Now connect the dots with a smooth curve. Is this path real or apparent? What do we mean by "real" and "apparent"? What would Earth's motion look like from Mars? Do the loops always occur at the same place in the planet's path? If not, why not?

Galileo was the first to look at the planets through a telescope. He observed that they not only changed position and direction, but also changed in brightness. He said that two of the planets "imitated the forms of Cynthia" (an ancient name for the Moon). How can planets, like the Moon, exhibit phases? Where would they have to be in relation to the Sun and Earth in order to produce a phase? Let's investigate this idea.

activity 17.5 *The forms of Venus*

Let's try to discover the conditions under which Venus shows a various phase to an observer on Earth. On a large table or on the floor, draw two large circles with a common center. In our model, the inner circle represents the orbit of Venus and the outer circle represents the orbit of Earth. At the common center of the circles, place a flashlight to play the role of the Sun. Darken the room. Place a ball somewhere on the circle representing the orbit of Venus and adjust the flashlight so that it shines on "Venus." Place another ball at various positions along the circle representing the orbit of Earth. Squint across the top of "Earth" at "Venus." For us to see Venus in a crescent phase, where must Earth be, relative to Venus? From what position does Venus appear to be largest? Is this the same position from which it appears to be brightest?

CHECK YOUR FACTS

1. How do we indicate position along the celestial equator?
2. How do we indicate position north or south of the equator?

(2) (2) **ANSWERS** / Check Your Facts

1. Hours of ascension = horizontal angle.
2. Angular degrees North or South.

COMETS, METEORITES, AND ASTEROIDS

The world of comets. As fast as a comet! Do comets really zip across the sky? This impression, held by many people, is simply not true. A comet, like a planet, orbits around the Sun. Its orbit is very elliptical. Nevertheless, it moves around the Sun under the influence of gravitation, returning to its master perhaps only once in a hundred years. **(1)**

Comets are made up of a conglomerate of ices, with small solid particles embedded in the icy nucleus. Through a telescope a comet looks like a fuzzy star. When close to the Sun, it stretches its feathery plume of gas and solid particles across the sky. This **comet tail** always points away from the Sun; it also grows longer as the comet approaches the Sun (Figure 17.13). What do you think causes comet tails to point away from the Sun? (Hint: What causes Earth's magnetic field to be distorted, as shown in Figure 1.4?) **(2)**

From prehistoric times men have been frightened by the appearance of comets and thought they represented omens of the worst kind. What are these strange ghostly bodies and where did they come from? The origin of the comets remains a mystery, but most scientists believe they are material left over after the formation of the solar system. Others believe that they may be part of the wreckage of planets that collided.

Most comets consist of two parts, the head and the tail. The **comet head**, which may be as much as 150,000 kilometers across, is a large luminous envelope of gas and dust. Some have been reported to be as large as the Sun. Extending from the head is the vaporous tail, which may reach a length of about one astronomical unit. Halley's comet, the best known of all comets, has a tail even longer than this.

What is the largest body in the solar system? The answer to this depends on what we mean by "large." The dimensions of some comets are large; but their mass is small. Some astronomers estimate that a typical comet may have only a trillionth the mass of Earth. What can you say about the density of comets?

Each year new comets are seen, and some old ones return. About a third of all those sighted have been seen before on previous trips around the Sun. Comet observations can be an exciting hobby—particularly because a comet is named after the person who discovers it! Two young Japanese—a guitar player named Ikaya and a piano tuner named Seki—have between them five comets to their credit. One, which they both observed the same night, was given the name Ikaya-Seki. If

Figure 17.13 Can you tell from this photograph which way the comet is moving? Can you tell which direction the Sun is in? **(3)**

(1) Ask students to find out the properties and dates of Halley's Comet (1985-1986).

(2) Radiant energy exerts a force (pressure) which pushes the tails of comets away from the sun. Some comets have no tails and some have more than one.

(3) We can't tell which way the comet is moving, but the tail points away from the sun.

you were the first to find an unknown comet and reported it to the proper authorities, it would be given your name.

Because they lack even a solid surface to land on, it is obvious that comets do not provide a possible environment for man. Comets do, however, influence man's environment on Earth. When they come close to Earth, they provide some of the material for meteor showers, better known as "shooting stars."

Meteorites. Except for pieces of the Moon brought back by astronauts, meteorites are the only extraterrestrial objects man has been able to observe in the laboratory. ("Extraterrestrial" means "originating outside Earth".) These exotic visitors sometimes explode when they strike Earth's surface, producing some dramatic craters (Figure 17.14). Other meteorites bury themselves several meters in the ground. A meteorite that fell in a cornfield in Kansas is estimated to weigh over (4) one ton.

Often there is confusion over the terms used to describe these visitors from space. The word **meteor** is used to describe the bright streak of light that flashes across the sky. Meteors have been called "shooting stars." Perhaps you have even made a wish after having seen one. A meteor is actually the light given off when a piece of stone or iron called a **meteoroid** zips into Earth's atmosphere and burns up by friction with the air. When a meteoroid is large enough so that part of it sur-

(4) There are three basic types of meteorites: (a) iron and nickel—analogous to Earth's core, (b) iron, nickel, and silicate mineral—analogous to Earth's mantle, and (c) a stony (silicate) form—analagous to Earth's crust.

(5) (a) erosion, (b) erosion is slower on the Moon that on Earth, (c) erosion has not obliterated them.

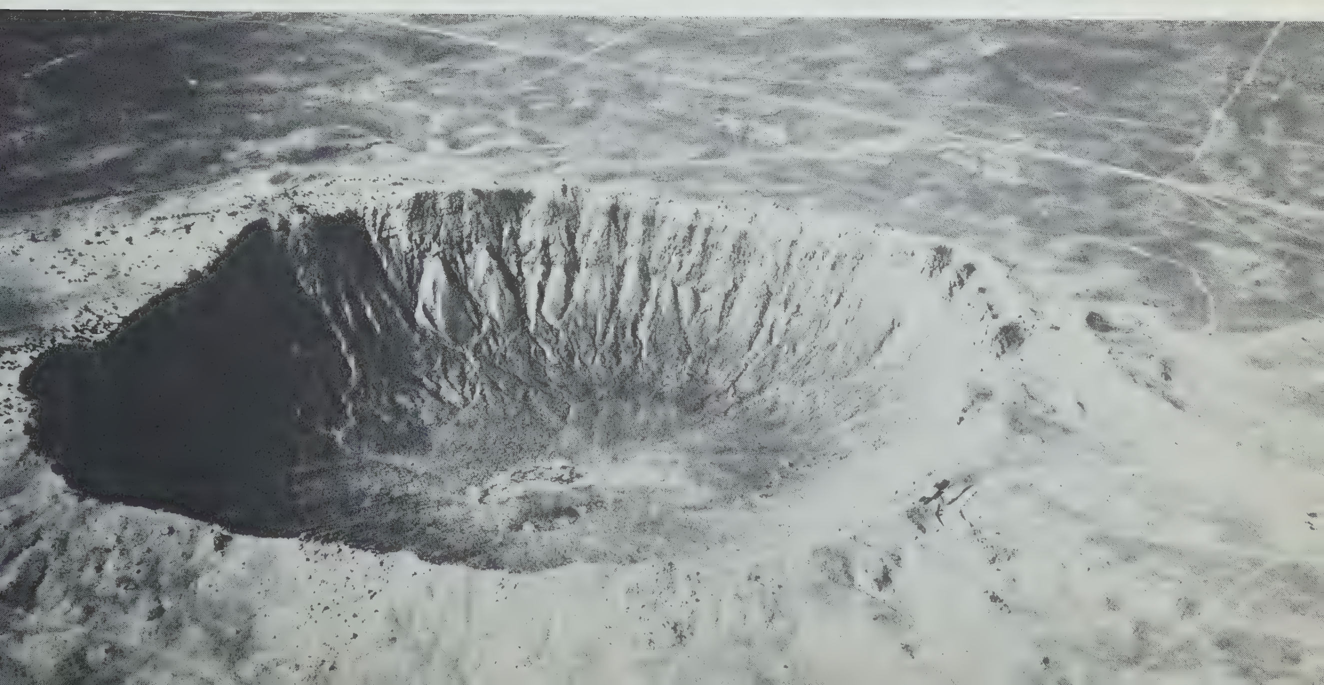


Figure 17.14 This crater in Arizona, more than a kilometer in diameter, was produced by the explosive impact of a meteorite. In about ten million years—a short time by geological standards—the crater will be gone. Why? On the Moon, one footprint would probably exist that long. Why? Can you think of a reason why so many craters exist on the Moon's surface and so few on the surface of Earth? (5)

vives the journey to Earth's surface, we call it a **meteorite**. Where are you more likely to find meteorites—on Earth or on the Moon? (1)

When and where do you look for meteors? Do they occur simply by chance, or is there some time pattern to their appearance? Most meteoroids travel in swarms around the Sun, and are commonly associated with comet orbits. At certain times during the year, Earth intercepts these belts of material. When this debris collides with Earth it produces a **meteor shower** and we see more meteors than we usually do. (2)

More meteors are seen after midnight than at any other time. Why? (Hint: Why do insects splatter on the front windshield of a moving car but not on the rear window?) (3)

(1) Should be more common on the Moon because of the Moon's lack of an atmosphere to consume them (friction).

(2) See data table in the Commentary, page T20.

(3) At midnight, Earth's rotation is carrying you in the same direction (east) as Earth's revolution is carrying you. You are then looking out the front windshield, so to speak.

Asteroids. Thousands of small bodies called **asteroids** orbit around the Sun. Most of their orbits lie between the orbits of Mars and Jupiter. Some scientists have suggested that asteroids (like meteoroids) are fragments of planets that collided. If this were so, we would expect the total mass of all the asteroids to be something near the mass of a planet. However, it is believed that the total mass of the asteroids is less than 5 percent of the mass of our Moon.

If you landed on an asteroid, you would have every reason to say to your fellow astronauts, "It's a small world, isn't it?" Some asteroids are only a few kilometers in diameter. Ceres, named for the Roman goddess of harvest, is the largest asteroid known. It is 770 kilometers in diameter. Do you think man could live on Ceres? What would it be like there? Do you think we would find life on Ceres?

Our search for life so far has not met with success. Perhaps, to find life, we shall have to go to the planetary system of some other star. At present this is not possible, but don't underestimate man's ability! One day, man may look upon some landscape illuminated by light from some star other than the Sun.

CHECK YOUR FACTS (4)

1. Do comets orbit around the Sun?
2. Which way does a comet's tail point?
3. Where are asteroids found?

(4) **ANSWERS** / Check Your Facts

1. Yes, in a long, eccentric elliptical orbit.
2. Away from the sun (as a result of radiation pressure).
3. Mostly between the orbits of Mars and Jupiter.

APPLYING WHAT YOU HAVE LEARNED

1. What are the basic essentials for life as we know it?

2. Why is it presently impractical for man to consider a trip to investigate the environment of the star Proxima Centauri?

3. Explain how the "greenhouse effect" affects the temperature on Venus.

4. Do we have evidence that Mars really doesn't have canals?

5. Explain how planets such as Mars can reverse direction (loop) against the background of stars.

6. Why is it unlikely that we will find complex life forms on Mars?

7. How is it possible for Jupiter to produce more energy than it receives from the Sun?

8. How do the phases of Venus compare to the phases of the Moon?

9. Do planets farther from the Sun than Earth is exhibit the same phases as do Mercury and Venus?

(5)(5) **ANSWERS** / Applying What You Have Learned

1. The elements C, H, N, O, S. (Any elaboration of this answer will be acceptable.)
2. Our life span is not great enough to cover such distances at the speeds we can presently accomplish.
3. It makes Venus hot.
4. Yes—the Mariner films.
5. They don't, but the relative positions of Earth and Mars cause apparent looping.
6. The extreme conditions on Mars militate against the existence of complex life forms as we know them.
7. By radioactive disintegration in its interior.
8. They are much the same.
9. No.

KEY WORDS

principle of uniformity (p. 333)
Proxima Centauri (p. 334)
astronomical unit (p. 337)
celestial sphere (p. 346)
celestial equator (p. 346)
comet tail (p. 350)
comet head (p. 350)
meteor (p. 351)
meteroid (p. 351)
meteorite (p. 352)
meteor shower (p. 352)
asteroid (p. 352)

Figure 18.1 Gigantic disturbances known as prominences can be seen all around the Sun in this photograph.

Introductory Demonstration

On a clear day with the sun visible, you will need a small telescope and a projector screen or a large sheet of cardboard.

Caution: Don't look at the sun and warn your students of possible eye damage from direct viewing of the sun.

Carefully point the eyepiece of the telescope in the direction of the sun. Watch for the bright image to fall on the screen. Hold a piece of thin paper in the path of the image. It will catch fire. This will show your class how much energy comes through that eyepiece. (You might even light a cigar.)

Be sure that the entire class can see the projected image of the sun in focus on the screen. Indicate the positions of sunspots and other features. This is a very dramatic demonstration and captures the students' interest.

chapter 18

The Sun—The Star We Know Best

What is the Sun? A burning rock? A glowing disk of steel? Or is it the flaming carriage of Apollo, the Greek god of light?

If you ask a modern astronomer what the Sun is, he would probably answer that it is a gigantic ball of very hot gas. Indeed, its diameter is almost 1,400,000 kilometers—more than a hundred times the diameter of Earth. The entire Earth-Moon system could be put inside the Sun with lots of room left over. (The diameter of the Moon's orbit around Earth is almost 800,000 kilometers.)

But the inside of the Sun is not exactly the best place to move our Earth to. The terrible temperature of several million degrees would vaporize Earth much as boiling water melts an ice cube tossed into it. Each square meter of the Sun's surface radiates 15 million calories of energy per second. It would take 400 cars with their engines running full blast to produce energy at such a rate. The *total* energy output of the Sun is about

7 billion billion times greater! In a single second, the Sun radiates more than enough energy to make all our oceans, lakes, and streams boil.

Obviously, the Sun is the most important heavenly body to us. It keeps the planets, including Earth, in their orbits. Without its radiation life on Earth would die. (Where does our food come from? Remember photosynthesis from Chapter 12?) (1) But to an astronomer, the Sun is also important for another reason: It is a star. While other stars are so far from us that they appear only as pinpoints of light even through the largest telescopes, the nearby Sun can be explored in detail. By learning its properties and behavior, astronomers can make intelligent guesses about what other stars are like. (2)

(1) Photosynthesis is the manufacture of carbohydrates by green plants. Carbon dioxide and water in the presence of chlorophyll and energy (from the Sun) make glucose and oxygen.

(2) Refer here to an overhead transparency of the Sun. Those available from Hubbard and Hammond are excellent.

WHAT IS THE SUN LIKE?

To explore the Moon or the planets, we can go there or send (3) scientific instruments to do the job. But can we go to the Sun? Wouldn't we be vaporized by heat as we came near it? How, then, can we learn about the Sun? How do we know, for instance, that it is a ball of gas and not a superhot disk of steel? (4) How can we figure out its distance, size, and temperature? Do we know where the Sun gets its energy? Will it shine forever, or will it eventually burn out, like a log in a fireplace? These are some of the questions we shall touch on in this chapter.

(3) Obviously we can't go to the Sun to study it, but we can observe it by projecting its image on a screen and by studying its spectrum. Stress that under no circumstances should the Sun be observed with the naked eye.

(4) At the surface temperature of the Sun (5600°C), all the chemical elements exist in the gaseous state.

How far away is the Sun? You learned in the last chapter that the distance from Earth to the Sun (one astronomical unit) is about 150 million kilometers. How do we know this?

How do you measure the distance to an object in the (5) heavens? One way is to bounce radar waves off it. We know that radar waves travel at the speed of light (about 300,000 kilometers per second). By measuring the time it takes for a radar wave to get there and for its echo to come back, we can figure out the distance to the object. (Do you see how?) In (6) recent years laser beams have been used to measure distance. The distance to the Moon, for example, has been measured very accurately by bouncing a laser beam off a shiny reflector that was placed on the Moon's surface by Apollo astronauts.

Can we measure the distance to the Sun by this echo method? The answer is no. It's true that radar echoes from the

(5) Distance to many objects in space can also be measured by parallax, a triangulation method involving trigonometry.

(6) Radio waves make a round trip to the Moon in approximately 2.5 sec. Since they travel at the speed of light, the Earth-Moon distance is roughly 1.25 sec x 300,000 km/sec = 375,000 km (plus the radii of Earth and the Moon because the distance the radio waves travel is measured from surface to surface rather than from center to center).

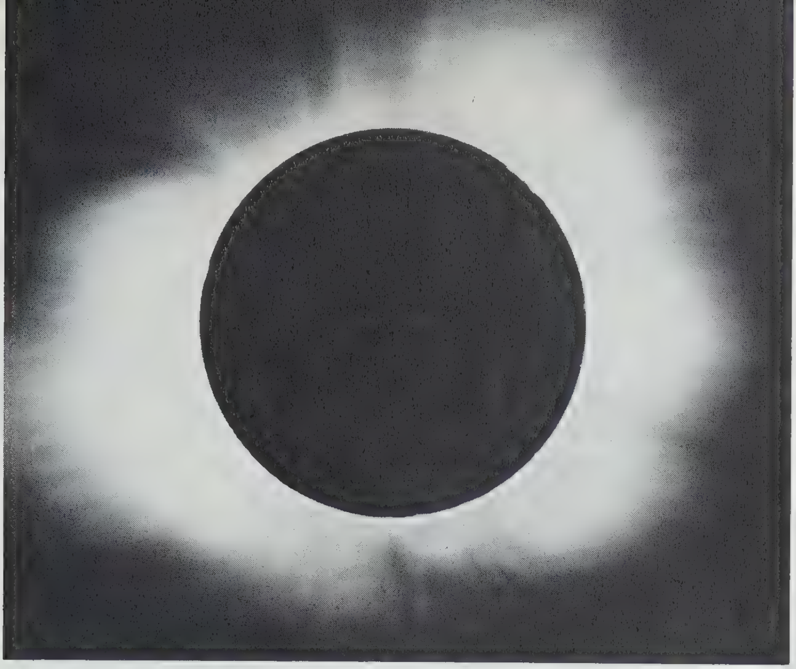


Figure 18.2 The Sun's corona can be seen clearly in this photograph taken during a total solar eclipse.

Sun have been received. But the trouble is that the Sun is surrounded by a **corona**—a huge envelope of very hot gas (7) (Figure 18.2). The radar echoes come from various regions in the corona rather than from the solar body itself.

(7) Why the solar corona is at a higher temperature than the solar surface is not fully understood.

But astronomers have found a way to overcome this obstacle. They have observed that clear radar echoes are received from nearby planets and asteroids on their close approaches to Earth—for example, from Venus and from the small brick-shaped asteroid Eros, which sometimes "grazes" Earth at the relatively close distance of 23 million kilometers. On such occasions, their distances can be measured with high accuracy.

It may come as a surprise to you that this seemingly unrelated fact can help astronomers measure the distance to the Sun. How can the measurement of the distance between Earth and another planet tell us anything about the distance between Earth and the Sun? The answer lies in a rule discovered by the German astronomer Johannes Kepler almost four centuries ago that relates the period of a planet to its average distance from the Sun. The period of a planet is the time it takes that planet to go once around the Sun. It can be measured easily. (The period of Earth is, of course, one year.) Let's call the period of a planet P and its average distance from the Sun D. P is measured in years and D is measured in astronomical units. The rule states that for every planet in the solar system

$$P^2 = D^3$$

In words, the rule says that the square of the period is always equal to the cube of the distance. That is, the number you get by multiplying the period by itself ($P \times P$) is always equal to the number you get by multiplying the average distance three times ($D \times D \times D$).

This rule was important historically because it enabled astronomers to make a scale model of the solar system. The model gives the distances in the solar system in astronomical units, but it does not give the distances in kilometers. However, if any one distance (such as the distance between two planets) is measured in kilometers, it can be used to tell us all the other distances (such as the distances of the planets to the Sun) in kilometers.

Let's take Venus as an example. Its period is 0.615 year. Since $0.615 \times 0.615 = 0.378$, the cube of Venus's distance must give the same value. The number that satisfies this requirement best is 0.723. Therefore, the distance of Venus from the Sun is 0.723 astronomical units. You can check it out by multiplying $0.723 \times 0.723 \times 0.723$. Do it!

Once we know the distance between Venus and the Sun in astronomical units, and once we have measured the actual Earth-to-Venus distance, it's an easy job to figure out the actual Earth-to-Sun distance. You can do it yourself! Surprised? The following activity will show you how.

activity 18.1 *Determining the distance to the Sun*

Figure 18.3 shows Venus and Earth in their orbits. Notice that the faster-moving Venus has passed Earth and is now making an angle of 40° with the direction to the Sun.

Draw a similar diagram on a larger scale. Since the orbits of Venus and Earth are almost circular, you can use a compass to draw them. For convenience, choose the radius of Earth's orbit equal to 10 centimeters and that of Venus equal to 7.2 centimeters. Then use a protractor to locate Venus 40° from the direction to the Sun.

Measure carefully the distance in your diagram from Earth to Venus. Compare the Earth–Venus distance to the Earth–Sun distance, which we have drawn equal to 10 centimeters. Which of the two is longer? How many times? Now, if radar echoes tell us that Venus is 69 million kilometers from Earth at this instant, how far is Sun from Earth? How long, then, is (1)

(1) Divide the Earth-Sun distance in our diagram by the Earth-Venus distance and multiply the quotient by 69 million. The answer will be in kilometers.

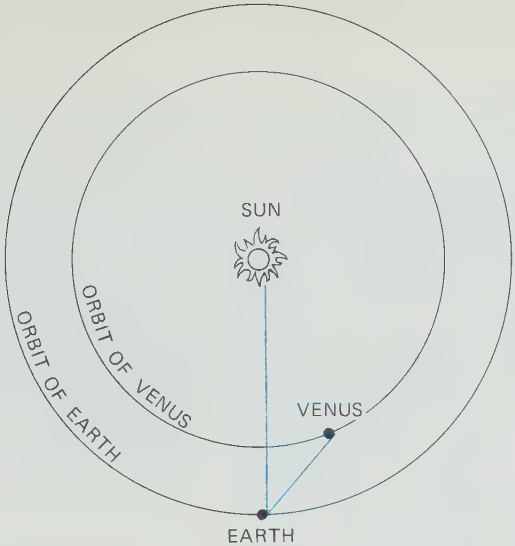


Figure 18.3 Measuring the distance to Venus by means of radar echoes allows us to also determine the length of the astronomical unit.

the astronomical unit? Do you see now how the distance to the Sun can be measured by clocking the roundtrip time of radio waves to Venus?

If, dressed in a protective asbestos suit, you could drive to the Sun at 100 kilometers per hour, how old would you be by the time you reached your destination? How long does it take sunlight to make the 150 million kilometer journey to Earth? (2)

(2) The distance covered in one year would be 100 km x 24hr/day x 365¼ days/yr, or 876,600 km/yr; 150 million km divided by 876,600 km/yr yields roughly 171 yr. Students should add their ages to this number.

How big is the Sun? Did you know that the size of the Sun can be measured by using a flower box? Here's how to do it.

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activity 18.2 *The Sun and the flower box*

Make a small circular hole at one end of a flower box and replace the other end with translucent paper, such as tracing paper (Figure 18.4). Then turn the box toward the Sun so as to get a circular image of the Sun on the translucent panel. You now have two long, thin triangles that are *similar*, or same in shape. Carefully measure the diameter of the image and the length of the box. The solar diameter can now be found from the two similar triangles:

$$\frac{\textbf{solar diameter (in km)}}{\textbf{150,000,000 km}} = \frac{\textbf{diameter of the image (in cm)}}{\textbf{length of the box (in cm)}}$$

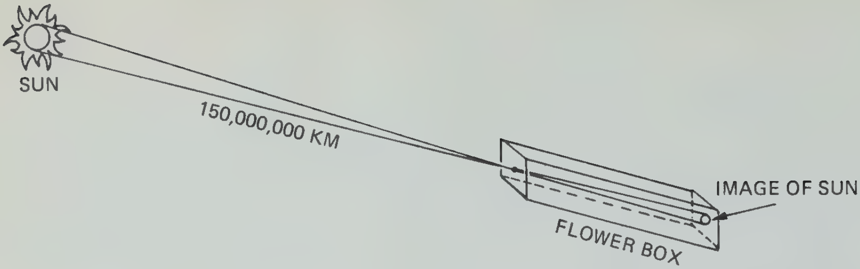


Figure 18.4 The size of the Sun can be measured by using a flower box or a paper carton. A long box or carton will give you a more accurate measurement than a short one.

Multiplying both sides of the equation by 150,000,000 km, we get:

$$\text{Solar diameter} = \frac{\text{diameter of the image}}{\text{length of the box}} \times 150{,}000{,}00\ \text{km}$$

If everything is done correctly, the result will be in the neighborhood of 1,400,000 kilometers. But don't be disappointed if it isn't. Your "astronomical equipment" was quite poor.

How many times larger is the diameter of the Sun than that of Earth? If Earth were reduced to a marble 1 centimeter in diameter, how tall would the Sun be? In a scale model of the solar system, the marble and the giant ball would have to be placed almost 120 meters apart!

(1)(1) Approximately 110 times.

(2)(2) Approximately 1.1 meters.

activity 18.3 The necklace in the sky

You can calculate the approximate size of the solar diameter in many ways. Let's try one more way.

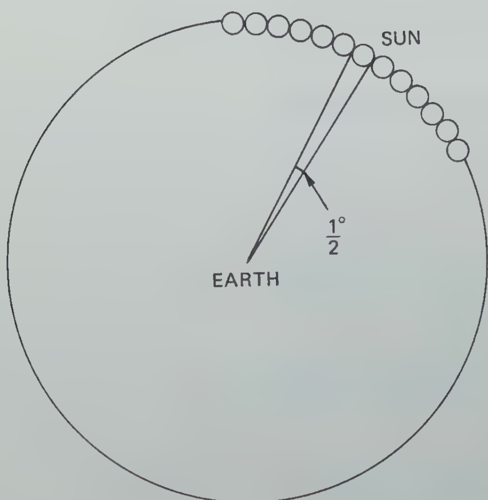


Figure 18.5 If you put "Suns" next to one another across the sky, you can make a necklace with many beads. This drawing is not to scale.

As seen from Earth, the Sun covers an arc of slightly more than $\frac{1}{2}$ degree. How many objects similar to the Sun could be placed in the sky next to each other, like beads in a necklace (Figure 18.5)? (Hint: There are two "Suns" per degree, and 360 degrees in a full circle.) Remembering that the distance to the Sun is 150 million kilometers, figure out the length of the "necklace" in the sky. (The circumference of a circle is $2\pi r$.) Can you now find the approximate diameter of one of the "beads," (3) the Sun? Does your result agree with the actual diameter of the Sun? Again, because the numbers we are using are rough, we should be satisfied if our result is close to being right. (4)

(3) 2 x 3.14 x 150,000,000 km = 942,000,000 km
942,000,000 km ÷ 720 (beads) = 1,310,000 km (the approximate diameter of the Sun).

(4) The Moon also has an angular diameter of ½°, so the Sun and Moon appear to be the same size in the sky.

"Weighing" the Sun. People unfamiliar with scientific methods of investigation often have doubts about astronomical measurements. "Who," they ask, "has ever been on the Sun in order to measure its size and mass?"

We just saw how the solar diameter can be figured out. "Weighing" the Sun is almost equally simple, although we will not do it here because it involves some mathematics that you have not had yet. Basically, it is a problem of determining the amount of gravitational force needed to keep a planet in an orbit. For example, to keep Earth in its orbit, the Sun must pull Earth away from a straightline path at a certain rate (just as Earth, in order to keep the Moon in its orbit, must pull it away from a straightline path at a certain rate, as in Figure 16.5). Figuring backwards, the astronomer asks himself: "How much force is needed to pull Earth away from a straight path at this rate? And how massive must the Sun be in order to produce this much gravitational force?" In this way it can be determined that the Sun's mass is about 2×10^{30} kilograms (2×10^{27} tons). This is a fantastic amount of matter. About 332,000 Earths could be made out of it. In fact, the Sun contains 99.85 percent of all the matter in the solar system. Out of the remaining 0.15 percent, all the rest of the solar system—the nine planets, their satellites, some 50,000 asteroids, and many comets and meteorites—is made. So you see, Earth is pretty insignificant, isn't it? (5)

(5) Earth would fit in the Sun's volume nearly 1.3 million times, and the mass of the Sun is 332,000 times that of Earth.

How hot is the Sun? On a hot summer day, the Sun makes blacktop roads so hot and sticky that it is impossible to walk on them barefoot; and its radiation gathered even by a small lens can burn your skin painfully.

The Sun must be a powerful celestial furnace to do all this. But how hot is it? And how do astronomers find out its temperature?

One of the clues to the Sun's temperature is its color. You might have noticed from your own experience that the color of a hot, glowing body depends on its temperature. What happens to the color of a heating element of an electric range as the temperature increases? Soon after you push the switch, the heating element starts glowing with a dull red light that changes gradually into red, then orange. If the temperature were increased still further (and the element didn't melt), it would turn yellow, then white, and eventually bluish-white. Thus, the temperature of a glowing body can be estimated from the color of its light.

What is the color of the Sun? Is it white or perhaps reddish, as suggested by the appearance of the rising or setting Sun? Not so. When watched from a distant point—from another star, for instance—the Sun would look yellow. Why?

To understand this, keep in mind that sunlight is not a single, pure color. Instead, it is a mixture of all the colors you see in a rainbow—red, orange, yellow, green, blue, and violet. A rainbow in the sky is the most magnificent example of the separation of sunlight into its component colors. We can produce the same effect by passing sunlight through a glass prism. The light will be spread out into a band of colors called a **spectrum** (Figure 18.10). All glowing bodies give off all the colors of the spectrum, but in differing amounts. As the temperature increases, the color that is emitted most strongly shifts from the red to the blue end of the spectrum. When we say the Sun is yellow, we really mean that, in the Sun's spectrum, yellow is stronger than all the other colors. For this to occur, the temperature of the Sun's surface must be about 5600° C. Thus, the Sun's color tells us the temperature at the Sun's surface.

But what about the solar interior? Is the temperature there higher, lower, or the same as at the surface?

Since the Sun emits heat, its inside must be hotter than its surface. You know from your own experience that heat flows from regions of higher temperature to regions of lower temperature. What does it feel like to make a snowball with your bare hands, or when you accidently touch a red-hot heating element? In which direction does heat flow in each case?

How much hotter is the inside of the Sun than the surface? The Sun is a great ball of gas, and gases expand when they are heated. You can demonstrate this to yourself with a balloon.

If you fill a balloon and then hold it at a safe distance above
a warm heating element, what happens to the size of the bal- (1)
loon? (And what would happen if you put it in a refrigerator?)

The heat of the Sun tends to make the Sun expand, but (2)
there is something else working in the opposite direction: gravitation. Gravitational force tends to pull every part of the Sun toward the Sun's center, making it smaller. We know that the Sun stays the same size, so we know that the forces tending to make the Sun bigger are in balance with the forces tending to make it smaller. The astronomer asks himself: "What must the temperature be inside the Sun in order for it to stay at this size—not so hot that it expands and not so cool that it shrinks?" The answer (which takes quite a lot of mathematics and physics) is that the Sun must be around 15,000,000°C at its central region. The temperature drops rapidly with increasing distance from the center to a "mere"
5600°C at the surface. Still pretty hot! (3)

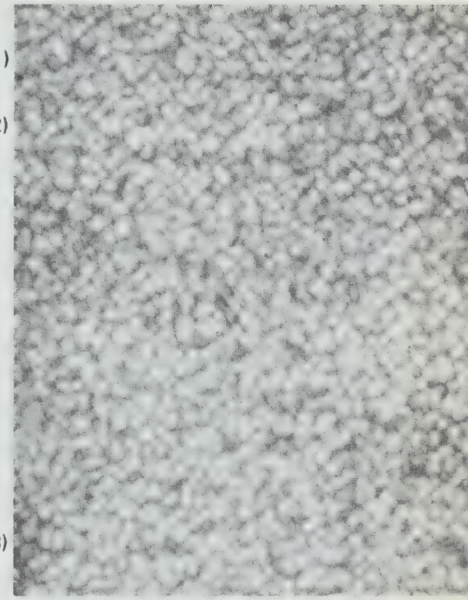


Figure 18.6 Many granules can be seen in this photograph of a small portion of the Sun's surface. Each granule is hundreds of kilometers across. The entire surface of the Sun is covered by granules.

(1) It would expand and burst.

(2) It would shrink.

(3) A visual aid showing cross section would be helpful (Hammond Transparency).

The Sun's surface. What is the surface of the Sun like? And how is it possible for a gaseous body to have a "surface" anyway?

Of course the Sun has no surface in the common sense of the word. There is no definite boundary between the solar body and the thin gases surrounding it. But that part of the Sun from which we see most of its radiation is usually referred to as the Sun's surface. It is surrounded by the solar atmosphere.

Caution **Never look at the Sun with unprotected eyes, even when it's close to the horizon and appears harmless! A dark or smoke-covered glass used by some people during solar eclipses is very dangerous because it does not block out harmful infrared radiation. A better way is to look through several layers of a fully exposed black and white (but not color) film. The safest method to watch the Sun, however, is to project its image through a telescope onto a screen.** (4)

(4) The Sun may also be observed by facing away from it and looking at the image cast by the Sun's rays as they pass through a pinhole in a three-by-five card onto a screen.

If a telescope is available, use it to project the image of the Sun onto a screen or a sheet of white paper. Does the solar surface appear to be perfectly clean?

A look at an image of the Sun projected through a good telescope shows you right away that the Sun's surface is covered with many elongated areas that look like grains of breakfast cereal. Known as **granules** (Figure 18.6), they come and go like bubbles on the surface of boiling water. Granules

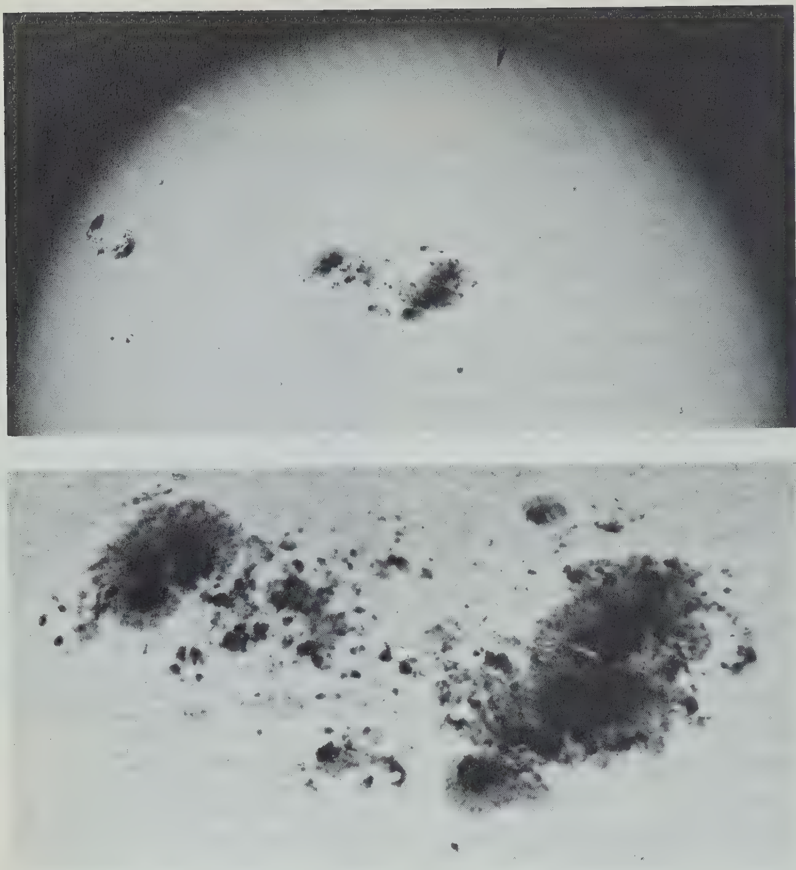


Figure 18.7 The top photograph shows a very large sunspot group. A more detailed view of this sunspot group is shown in the bottom photograph.

are believed to be huge columns of hot gases that rise from below the turbulent surface and then cool off quickly. Their lifetime seldom exceeds 10 minutes.

Features of the solar surface on a much larger scale are the **sunspots** (Figure 18.7). Starting their lives as hardly noticeable dark areas, many of them fade away within a few hours or a day. Others manage to survive the baby stage and may become large enough to be seen without a telescope. If lucky, they sometimes reach the "old age" of several months.

One of the largest sunspots on record reached 140,000 kilometers in length and 100,000 kilometers in width. That's an area of 14 billion square kilometers, or about 30 times the surface of Earth!

Although the central part of a sunspot looks almost black against the glaring surface of the solar disk, it is actually brighter than an electric arc! Sunspots appear dark because they are about a thousand degrees cooler than the surrounding area. If moved to a sunspot, you would be blinded by its light, killed by the deadly ultraviolet radiation, and barbecued by its heat.

(1) (1) There are many conditions here on Earth that are known to be related to the sunspot activity. Assign your students to investigate this.

(2) (2) An additional activity might be to determine the approximate diameter of a sunspot through a proportion. The projected image of the Sun is to the projected image of the spot as the true diameter of the Sun is to the true diameter of the spot.

(3) (3) The EBF filmstrip "Exploring the Sun" has an excellent series of pictures of one of the largest sunspot sequences.

The number of sunspots changes with time. While there are years when spots appear abundantly, at other times the solar disk is almost free of them. During the past century, the average length of a sunspot cycle (the interval between times of maximum sunspots) has been about 11 years, but on a number of occasions it has varied as much as 5 years either way of this value.

Brilliant eruptions known as solar **flares** are often seen near sunspot groups. Forces causing them must be enormous. It is estimated that one single large flare may release more energy than 100 billion atomic bombs! During the outburst of an intense solar flare, a great deal of ultraviolet radiation is released. Traveling at the speed of light, it reaches Earth about eight minutes later. Luckily, most of the deadly rays are stopped by our atmosphere before they reach the surface of Earth. But they cause great disturbances in the ionosphere, which normally reflects radio waves back to Earth. These disturbances interfere with long-range radio reception.

(4)(4) These are also responsible for the display of the Aurora (the northern and southern lights) here on Earth.

The Sun rotates, but how! Earth spins on its axis and so do the other planets and their satellites. But how about the Sun? Does it rotate? Or is it too big and dignified to move? And how could its rotation, if any, be detected?

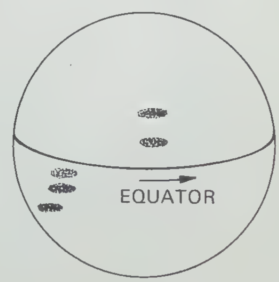
(5) The "movement" of the sunspots is actually caused by the rotation of the Sun.

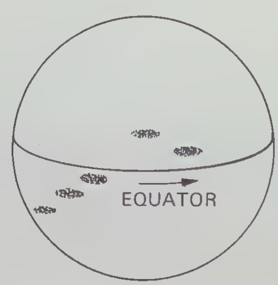
activity 18.4 Following sunspots

Compare the positions of the sunspots shown in the two drawings in Figure 18.8. The sunspots move in the direction of the arrows. The bottom drawing shows the positions of the sunspots about a month after the positions shown in the top drawing. The sunspots have moved completely around the Sun. But their relative positions have changed. Why?

Would you say that the Sun rotates the way a solid body does, or would you say that different regions of the Sun rotate at different rates? Explain your answer.

Figure 18.8 The top drawing shows the positions of an imaginary group of sunspots. The bottom drawing shows the positions of the sunspots about a month later. (5)





Above the surface. If you have ever seen a total solar eclipse, you know what an awe-inspiring experience it is. Many solar features that are invisible under normal conditions display all their splendor during the brief periods of the totality. The solar atmosphere is one of them.

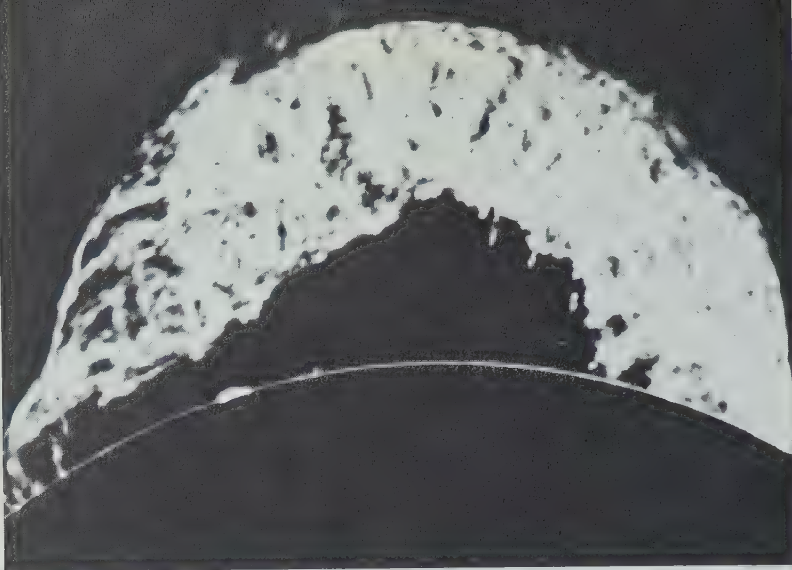


Figure 18.9 This famous, gigantic prominence occurred in 1946.

Made up of very thin gas, the atmosphere extends high above the Sun's surface. The lower 3500 kilometers of the atmosphere is called the **chromosphere**. Thinner than the best vacuum you can obtain in your science laboratory, but much hotter than the solar surface itself, this part of the atmosphere is in a constant turmoil. Above the chromosphere is the corona. When it appears at the moment the Sun's becomes completely covered during a total solar eclipse, it makes even experienced astronomers breathless. Its fine streamers may extend more than a million kilometers above the Sun surface. Although only half as bright as the full Moon, it glows beautifully on the dark background of the sky with the black lunar disk at its center (Figure 18.2).

In addition to revealing the corona, total solar eclipses sometimes also reveal another spectacular feature—the **prominences**. They are huge gas formations ejected from the (1) Sun by violent forces (Figure 18.9). Several prominences are visible around the Sun's disk in Figure 18.1. The great arches of gas burst from the solar surface and then, under the influence of gravitation, fall back into the Sun.

(1) Prominences at times rise more than 400,000km above the surface of the Sun.

CHECK YOUR FACTS (2)

1. Can we measure the distance to the Sun by bouncing radar waves or laser beams off its surface?

2. What is the mathematical relationship between the period of a planet and its distance from the Sun?

3. Where is most of the matter of the solar system located?

4. What color is the Sun?

(2) **ANSWERS** / Check Your Facts

1. No. Radar waves are reflected by the solar corona rather than by the solar "surface."
2. $p^2 = D^3$ [The square of the period (p) is equal to the cube of the average distance (D), provided the period measured is in years and the distance in AU.]
3. About 99.85% of the mass of the solar system is located in the Sun.
4. When viewed from a distance of several light years, the Sun appears as a yellow star.
5. The interior.
6. Indirectly—by watching its image on a screen.
7. Corona and prominences.

5. Which is hotter—the Sun's surface or its interior?
6. What is the safest way to observe the Sun?
7. What solar features can be seen during totality?

SPECTRA—FINGERPRINTS OF ELEMENTS

All of us enjoy colors. The world would look dull if everything—the sky, lawns, flowers, dresses—suddenly became colorless. The sensation of color is actually caused by **electromagnetic waves** as they strike your eyes. Whether you see blue, green, or red depends on the length of these waves.

Electromagnetic waves travel at the speed of light. Human eyes are able to detect electromagnetic waves with wavelengths ranging from about 3900 angstroms (violet light) to about 7600 angstroms (dark red light). The other colors correspond to waves of intermediate length (Figure 18.10). But a great deal of solar radiation reaches us in waves either too short or too long to be detected visually. You cannot see ultraviolet light, X rays, radio waves, or infrared waves. Yet solar radiation contains all of them. To detect their presence, sensitive films or elaborate instruments, such as radio telescopes, are used.

Spectroscopy. Some light sources radiate energy at all visible wavelengths; others emit only a select group of waves. This fact has enabled physicists to develop a powerful branch of science known as **spectroscopy**.

The principal instrument used in light exploration is a **spectroscope**. Its main part consists of a triangular glass prism or a diffraction grating (a flat glass or plastic plate with thousands of parallel lines ruled on its surface). Both serve the same purpose—to separate light into its component colors.

Want to make your own spectroscope? This is how to do it.

Figure 18.10 Visible light is made up of electromagnetic waves. Different colors of light correspond to different wavelengths. Ultraviolet rays, X rays, and gamma rays are also electromagnetic waves, but their wavelengths are shorter than those of visible light. They belong to the left of this picture. Infrared rays and radio waves have longer wavelengths than those of visible light and belong to the right of the picture.

activity 18.5 Using your own homemade spectroscope

Get a cardboard or metal tube 15 to 25 centimeters long and 2 to 5 centimeters in diameter. Tape a plastic diffraction grating on one end. Cover the other end with black opaque paper and cut a straight slit, about 1 millimeter wide, in it. Make the slit roughly parallel to the grating lines (Figure 18.11). Turn the slit end of your spectroscope toward various light sources and tell what you see.

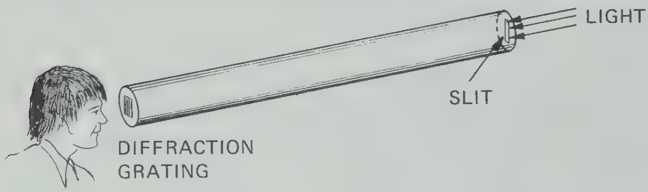


Figure 18.11 You can make a simple but useful spectroscope like this quite easily.

You can see that light emitted by an incandescent electric bulb or a red-hot paper clip gives spectra with all colors present. Such a spectrum is called a *continuous spectrum*. Continuous spectra are also emitted by hot gases under high pressure. But do all light sources produce continuous spectra?

Darken your laboratory room, place a screen with a narrow slit in the path of light (Figure 18.12), and use your spectroscope

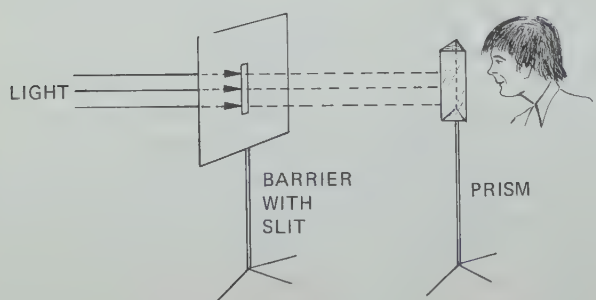


Figure 18.12 Look at various different sources of light with a setup like this.

or a glass prism to observe the spectrum of sodium gas. (You can obtain it by burning salt in the flame of a Bunsen burner.) If possible, also observe the spectra of a mercury lamp and a neon tube. What kind of spectra do you see? Are they continuous? Are they alike? (1) (2)

(1) To get a red flame, use the spectra of lithium or strontium obtained by heating lithium chloride or strontium chloride. For a range of green color use the spectra of copper, barium or boron. (Science Kit has a flame spectrum kit which works well.)

(2) Describe the spectra you see.

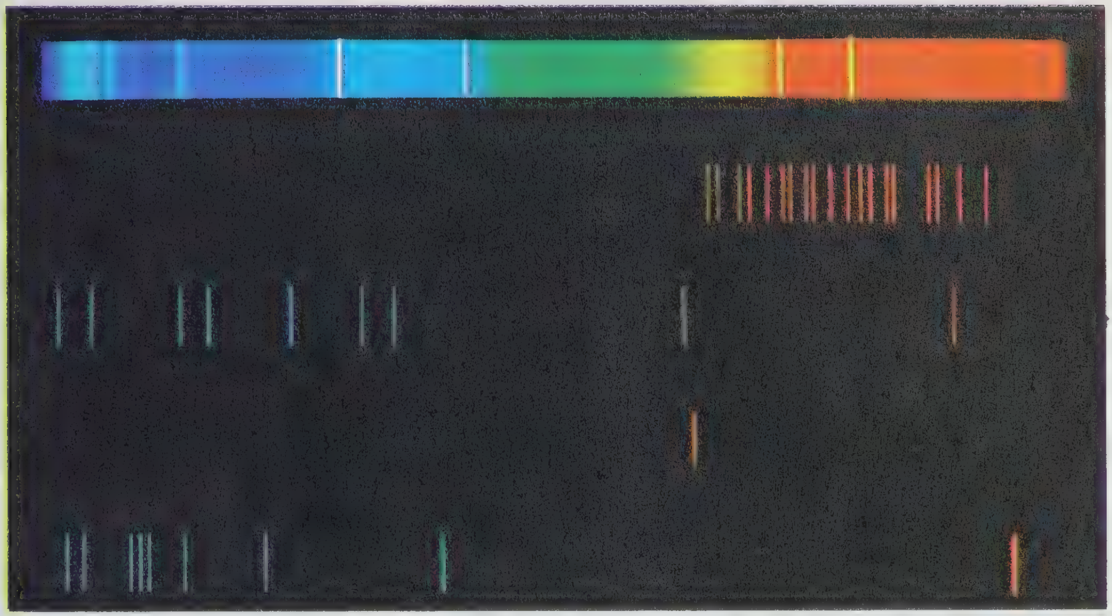


Figure 18.13 The spectrum at the top of this picture is produced by lithium. The spectra below it are produced by the gases neon, helium, sodium, and hydrogen (in that order). The yellow line of sodium shown here actually consists of two lines close together.

The conclusion is that luminous gases under normal or low pressure radiate light only in a few wavelengths. When you send the light through a spectroscope or diffraction grating, you do not get a continuous band of colors. Instead, you get separate colored lines on a dark background (Figure 18.13). All you can clearly see in a spectrum of a sodium gas, for instance, are two yellow lines. A glowing mercury gas produces a different set of lines, and so do other elements in a gaseous state. In fact, each chemical element has its own pattern of colored lines, a pattern shared by no other element.

Figure 18.14 If light that normally produces a continuous spectrum is allowed to pass through a relatively cool gas, the gas absorbs from it those wavelengths that it would emit if it were hot. The two dark lines here represent the wavelengths absorbed by sodium.

Spectra such as these, produced by glowing gases of chemical elements, are referred to as **bright-line spectra** or **emission spectra**. They can be likened to fingerprints of the various elements. By examining the spectral lines, an astronomer can tell the chemical composition of the light source even though he cannot actually go to the light source.

The story becomes even more intriguing when light that normally produces a continuous spectrum is allowed to pass through a relatively cool gas. What kind of spectrum do you think the light would yield? A continuous spectrum? An emission spectrum? Neither one. The pretty band of rainbow colors is now interrupted by a number of dark lines. The dark lines appear at places normally occupied by the bright emission lines of the intervening gas. Apparently, the intervening gas has absorbed those wavelengths that it itself emits when serving as a source of light. Known as **dark-line spectra** or **absorption spectra**, the row of dark lines tells us of gases (1)
encountered by light on its way to the spectroscope (Figure 18.14). (2)

The chemical composition of solid celestial bodies cannot be determined spectroscopically. Gases, however, are eager to disclose their secrets. If hot enough to radiate light, they make their presence and composition known by means of emission lines; when cool, they send messages by imprinting dark lines in the spectra of light passing through them. Always ready to cooperate, gases are a major source of astronomical information. (3)

(1) To put across the idea of an absorption spectrum, hold a colored filter (cellophane will do) in front of an incandescent light bulb and note the segment of the spectrum absorbed.

(2) Post a spectrum analysis chart in the classroom for reference. These charts are available from several chemical supply companies.

(3) The basic spectrum received from other planets in the solar system is a solar spectrum (reflected light).

The message of dark lines.

What stuff is the Sun made of? Is it a mixture of known chemical elements, or does it consist of elements not found on Earth? Previously you would have been puzzled by such questions, but not anymore. You have learned some spectroscopy, and it is going to help you.

Since the Sun is composed of highly compressed gases, its light contains all the wavelengths of the visible spectrum. But as light leaves the Sun, thousands of its wavelengths are absorbed by the gases of the solar atmosphere. By the time sunlight emerges from the chromosphere, it is not the same perfect light that left the solar surface just a split second earlier. Thousands of wavelengths are missing in it. When a spectroscope separates sunlight into its component colors, many dark lines appear in the spectrum (Figure 18.15). These dark absorption lines reveal the chemical composition of the solar atmosphere.

Figure 18.15 These strips of film show part of the spectrum of the Sun. The many dark lines in it can be clearly seen.


KODAK SAFETY FILM

To see how astronomers do their snoopy detective job, look at Figure 18.16. The light-colored band is a segment of the solar spectrum, with many dark lines. These lines are the "fingerprints" of the chemical elements in the solar atmosphere. They are the ones that carry the message. But how can astronomers tell which line belongs to which element? Don't they get lost in all these lines? Not quite. To find their way about, they use spectra of separate elements. For example, located alongside the solar spectrum in our photograph is the emission spectrum of iron vapor obtained in a laboratory. Iron's bright lines are clearly visible on the background. Compare the positions of lines in the two spectra. Can you find dark absorption lines opposite the bright emission lines of iron? If so, which element do you think has produced the dark lines? What conclusion can you make? (1)

In this manner, many elements have been detected on the Sun. It is estimated that 96 to 99 percent of the Sun consists of hydrogen and helium, with hydrogen being by far the predominant element. The rest of the solar body is made up of sprinkles of other elements, such as oxygen, nitrogen, carbon, and neon.

But isn't there a possibility that the Sun contains elements unknown on Earth? From what we know today, the answer seems to be no. About a century ago, however, astronomers (2) believed they had found one. During a total solar eclipse in 1868, they noticed a brilliant yellow line in the spectrum of the corona related to none of the already known elements. There was no doubt that signs of a hitherto unknown gas had been detected. The new element was named helium, after the Greek word for the Sun, *helios*. But 26 years later, an unfamiliar gas was discovered on Earth. When examined, it turned out to be the same helium astronomers had already found on the Sun, 150 million kilometers away and a quarter of a century earlier!

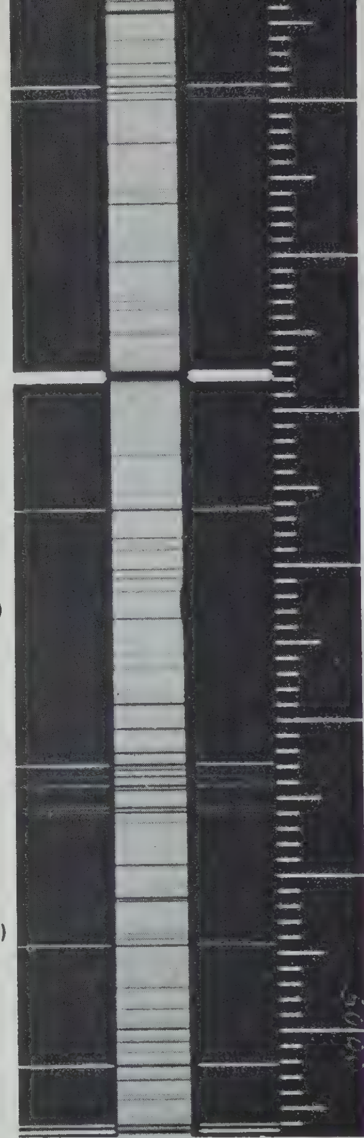


Figure 18.16 To find out which dark lines in the solar spectrum are the lines of iron, match it up with an emission spectrum of iron obtained in the laboratory.

(1) The fact that known absorption lines are not found where they belong (measured in the laboratory) indicates that the source is moving. (See the discussion of the Doppler shift in Chapter 19.)

(2) No fewer than 67 different chemical elements have been identified in the solar spectrum.

CHECK YOUR FACTS (3)

1. What are some kinds of electromagnetic radiation that the eye cannot see?

2. How is a bright-line spectrum produced?

3. How is a dark-line spectrum produced?

4. What kind of information can we get from dark-line spectra?

(3) ANSWERS / Check Your Facts

1. Infrared, ultraviolet, X rays, radio waves.

2. By heating chemical elements to incandescence.
3. By passing light with a continuous spectrum through a relatively cool gas.
4. The dark lines tell us the chemical composition of the intervening gas.

THE LITTLE EQUATION THAT MADE HISTORY

We said earlier in this chapter that the Sun radiates in a single second more than enough energy to make all our oceans, lakes, and streams boil. Where does the Sun get its energy to shine at such an extravagant rate for billions of years? For centuries, no one could answer this question.

Einstein's equation. The answer began to take shape in the early 20th century, when Albert Einstein (Figure 18.17) came forth with a startling idea: Matter, he said, is nothing absolute; it is just a special state of energy! Einstein expressed the relationship between energy, E, and matter, m, by means of a simple little equation:

$$E = mc^2$$

In this equation, c stands for the speed of light measured in centimeters per second ($c = 3 \times 10^{10}$ cm/sec); energy is measured in a unit called *erg*; and mass is measured in grams.

Who would have guessed that three such different things as energy, matter, and the speed of light are so closely tied! But the innocent-looking little equation tells us something else; it shows what huge amounts of energy are stored in matter. If in some magical way a gram of rock, ice cream, or hamburger could be made to vanish as matter, energy would emerge instead. How much? Einstein's formula yields the answer:

$$\begin{aligned} E &= mc^2 \\ &= 1 \times (3 \times 10^{10})^2 \text{ ergs} \\ &= 3 \times 10^{10} \times 3 \times 10^{10} \text{ ergs} \\ &= 9 \times 10^{20} \text{ ergs} \end{aligned}$$

Nine with twenty zeros is an impressive number, but how much of energy does it actually represent? The erg is a small unit; it is about equal to the energy carried by a slow-flying mosquito. When a mosquito lands on your forehead you may not even notice it unless the little robber decides to have a late evening meal. But the situation would turn more serious if 900,000,000,000,000,000,000 mosquitoes struck your forehead simultaneously. The energy carried by this many flying beasts equals a day's output by a small power plant.

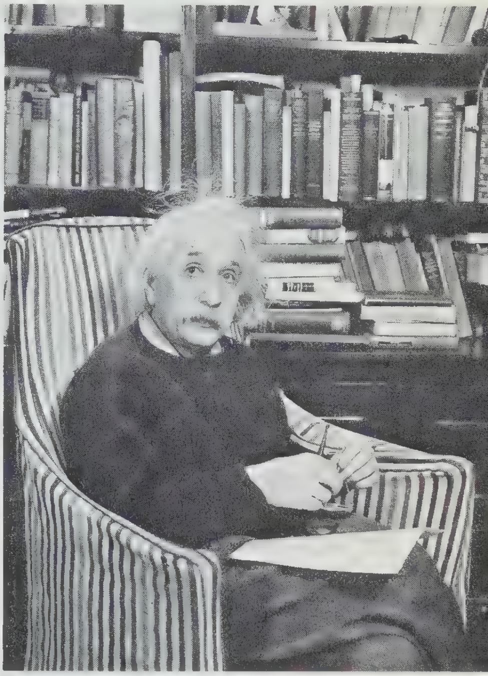


Figure 18.17 Albert Einstein.

The solar power plant. Einstein's equation suggested that the Sun might derive its energy from atomic reactions taking place deep in its hot interior. Astronomers knew al-

ready that the two most abundant elements in the Sun were hydrogen and helium. Couldn't it be the transformation of hydrogen into helium that accounted for the energy generation? The idea turned out to be correct, but the transformation process itself remained a mystery until later in the 20th century. The steps in the transformation are too complicated to describe here, but the net result is that four protons (hydrogen nuclei) are combined to form one nucleus of helium. But where does energy generation enter the picture?

The mass of one proton is about 1.008 amu (atomic mass units). The mass of a helium nucleus is almost four times as great: 4.003 amu. To form one helium nucleus, four protons are needed. A somewhat simplified bookkeeping of the reaction goes like this:

four protons being combined	4.032 amu
the emerging helium nucleus	4.003 amu
surplus mass	0.029 amu

It is this surplus that is converted into energy and makes the Sun and its sister stars shine.

The Sun and other stars have to pay dearly for their brilliancy. They do so at the expense of their mass. Since yesterday, the Sun has used up 370 billion tons of its mass, and it is going to lose a similar amount of mass during every 24 hours to come. But don't panic! Sun's hydrogen supply is so vast that it will be able to supply our planet at the present rate of energy for at least another 5 billion years.

(1)(1) This reaction is usually referred to as a fusion reaction.

CHECK YOUR FACTS

1. What is the equation relating energy, mass, and the speed of light?
2. How is energy generated in stars?

(2)(2) **ANSWERS** / Check Your Facts

1. $E = Mc^2$ where E is energy (measured in ergs, M is mass (measured in grams), and c is the speed of light (measured in cm/sec).
2. By the transformation of hydrogen to helium. The surplus mass as calculated is transformed into energy according to the Einstein equation.

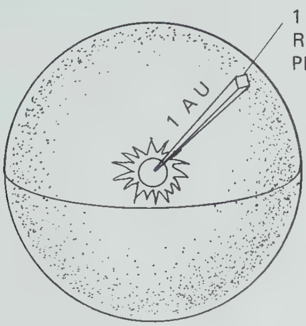
APPLYING WHAT YOU HAVE LEARNED

1. How do we know that the temperature inside the Sun must be higher than on its surface?
2. Mention some features on the Sun that we cannot see on other stars.
3. Each square centimeter on Earth, when placed at right angles to sunlight, receives 2 calories of energy per minute.

(3)(3) **ANSWERS** / Applying What You Have Learned

1. Since the Sun radiates heat, there must be a heat flow from its center toward its surface. Heat energy is known to travel from areas of higher temperature to areas of lower temperature; therefore, the interior of the Sun must be hotter than the surface.
2. Granules, sunspots, solar flares, chromosphere, prominences, and corona.

Imagine a huge ball, 1 astronomical unit in radius, drawn around the Sun (Figure 18.18). The total area of this ball is about 3×10^{27} square centimeters. What is the total amount of energy put out by the Sun in one minute?



4. How do astronomers know that the Sun is a ball of gas rather than a disk of glowing steel?

5. What do X rays, infrared rays, visible light, and radio waves have in common?

6. What can we learn about the Sun by examining its spectrum?

7. Describe steps you would follow to find out whether sodium vapor can be found in the solar atmosphere.

8. Are nuclear reactions taking place in the interior of Earth? Explain your answer.

9. The Sun is a mighty powerhouse, but can it move mountains on Earth? Explain your answer.

KEY WORDS

corona (p. 357)
spectrum (p. 362)
granule (p. 363)
sunspot (p. 364)
flare (p. 365)
chromosphere (p. 366)
prominence (p. 366)
electromagnetic wave (p. 367)
spectroscopy (p. 367)
spectroscope (p. 367)
continuous spectrum (p. 368)
bright-line spectrum (p. 370)
emission spectrum (p. 370)
dark-line spectrum (p. 370)
absorption spectrum (p. 370)

3. 6×10^{27} calories.
4. They know that all the chemical elements are in the gaseous form at the temperature of the Sun's surface.
5. They are all electromagnetic waves.
6. The chemical composition of its atmosphere.
7. (a) Obtain a solar spectrum; (b) obtain a sodium spectrum (in a lab); (c) compare the two spectra. Dark absorption lines in the solar spectrum opposite the bright emission lines in the sodium spectrum indicate the presence of sodium in the solar atmosphere. (Note: a failure of the dark absorption lines to appear in the spectrum of the Sun would not necessarily mean the absence of Na in the solar atmosphere. It may be there in such small quantities that they are insufficient to imprint the dark lines.)
8. No. The core of the earth is not hot enough to trigger such reactions.
9. Yes. Solar heat produces erosion and wind, both of which can be said to move mountains.

Figure 19.1 The Orion nebula, a glowing body of gas in the Orion constellation, is barely visible to the naked eye.

Introductory Demonstration

The best and most enlightening experience students can have as an introduction to Other Stars is to observe a demonstration in a local planetarium showing the constellations and the star field at different times and at different latitudes. If a planetarium is not available, plan a field trip at night, well chaperoned and equipped with student telescopes; a most enlightening experience.

chapter 19

Other Stars

Viewed in the night sky, the stars appear to us as tiny points of light. It is hard to believe, but each of these stars is similar in its basic nature to our own blazing Sun. The stars look so different only because they are so unimaginably far away.

Of course even the brightest light source would appear faint if moved to a large enough distance. Even in ancient times, astronomers believed that the stars were much farther away than the Sun and the planets. But exactly how far? For centuries, one guess was as good as another. Only in the nineteenth century did astronomers find a way to actually measure the distances to the stars. They found to their amazement that the *nearest* stars are tens of trillions of kilometers away! And most stars are at even greater distances; some are millions of times farther than the nearest stars. These results showed that the stars must indeed be mighty powerhouses like the Sun if they are to be seen at all from Earth.

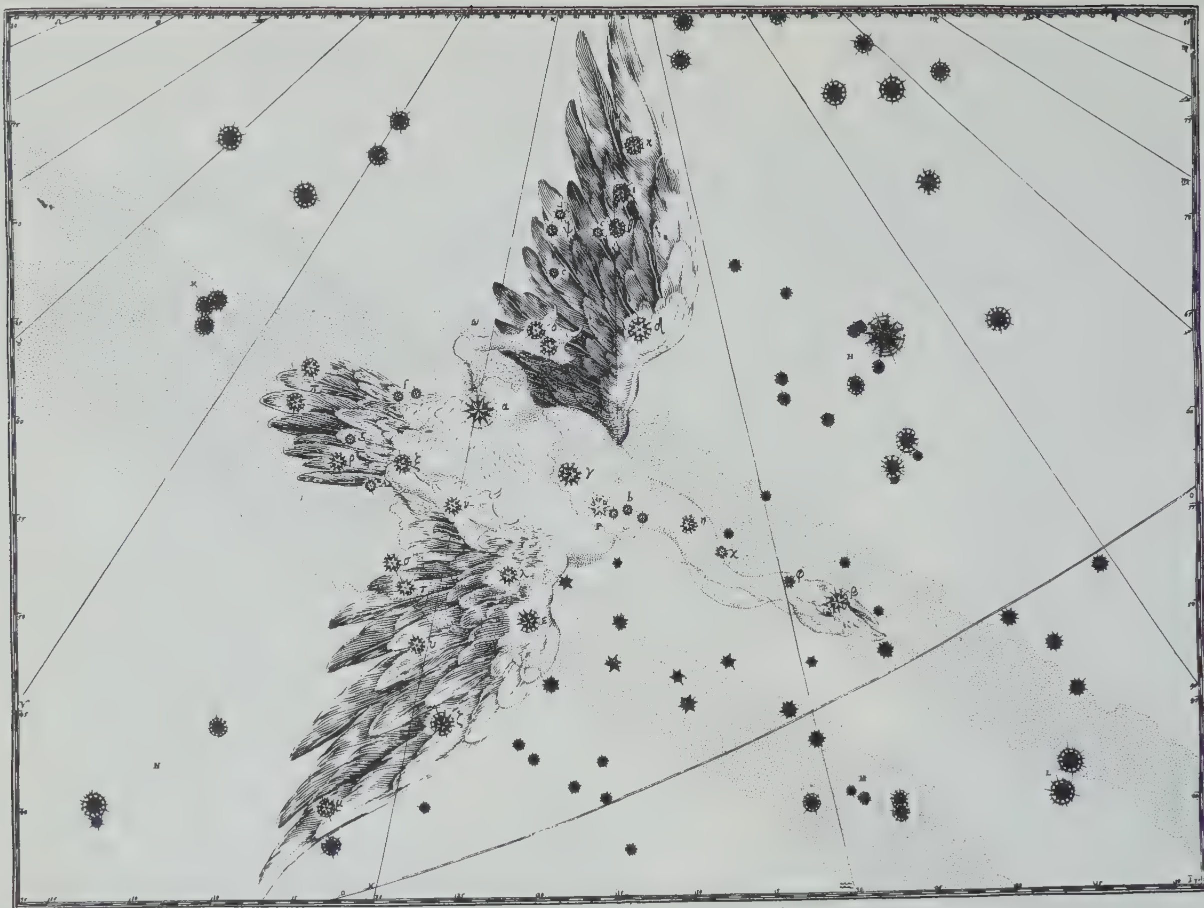


Figure 19.2 The constellation Cygnus, or the Swan.

GETTING ACQUAINTED WITH STARS

In their variety, the stars are like the students in your class; you all have much in common, yet each of you is unique. All stars are great balls of hot gas held together by their own gravitation and they all radiate light and other kinds of energy. But they differ greatly in their sizes, densities, and the rate at which they give off light. Compared to this stellar variety, the Sun turns out to be an ordinary, run-of-the-mill star, neither especially large nor especially small.

Light from the Sun reaches us in only about eight minutes,(1) but light from the nearest star (remember which?) takes more than four years to make its trip through space. The stars are so far away that it makes sense to measure their distances in terms of the time it takes light to travel from them to us. Light is a good measuring stick because it always travels at the same speed: 300,000 kilometers per second. The distance light(2) travels in one year is called a **light-year;** it is nearly ten tril-

(1) Proxima Centauri is the nearest star beyond the Sun. Refer to this in Chapter 17.

(2) This, of course, is true, providing the velocity is measured within the same medium. (Its velocity is different through air, water, and space, although constant in each.)

lion kilometers. A typical stellar distance is many hundreds of light-years; light from such a star left the star hundreds of years before we see it. Light (along with all other electromagnetic radiation) is the swiftest messenger in the universe; but if the message is from a star, we must wait quite a long time to receive it.

(3) **(3)** Ask a question something like: Near which star must you be to look back to Earth and the Moon and see Neil Armstrong first place his foot on the Moon's surface? (Hint: 1969 is how many years ago?)

Because of these long delays, you don't see the stars as they are today. Can you even be sure they still exist? Could new stars have come into being without your knowing it, because their light has not yet reached you? A view of the starry sky is like a collection of snapshots; the farther away a star is, the older its picture and the younger it looks. As you turn the pages of a photograph album, faces of your friends and relatives smile at you, but you know well that none of them look today the way you see them in the photographs. So it is with the stars.

(4) **(4)** Can you imagine where you would have to be in order to look at Earth and see the first man? (*Homo habilis* lived about 1.72 million years ago.)

How far away are the stars? The first man to measure the distance to a star was a German scientist named Friedrich Bessel. The star, lying in the contellation of the Swan (Figure 19.2), was named 61 Cygni. How exactly did Bessel figure out the distance to his "lucky star"? And why hadn't astronomers been able to measure stellar distances before him? To answer the questions, let us first toy with a couple of simple observations.

Stretch your arm and watch the direction to your thumb, shutting first one eye, then the other one (Figure 19.3). Do you see the thumb in the same direction both times? Or does it appear to "jump" with respect to background objects, such as a lamp, a marking on a blackboard, or a picture hanging from a wall?

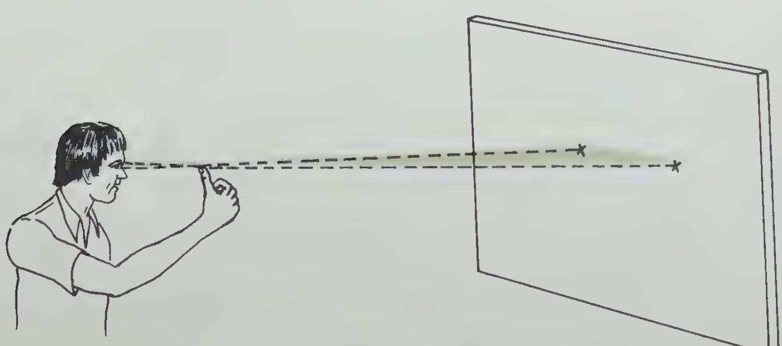


Figure 19.3 Viewed with one eye and then with the other, your thumb appears to change position.

Obviously, the direction to an object changes when viewed from different positions. One half of this change is called the **parallax** of the object you observe.

Now move the thumb closer to your eyes and observe what happens to the parallax. Does it increase, decrease, or remain unchanged? You conclude that distant objects have smaller parallaxes than the closer ones.

That was simple. But how about stars? Do they have parallaxes too? (1)

Watch a star alternately with one and then the other eye covered. You will not notice any change in its direction. But can we say that stars have no parallaxes? Or would it be more correct to say that stellar parallaxes are very small because stars are so far away from us?

Fortunately, a star's parallax does not depend on the distance alone. Think of what would happen to it if the star were viewed from two widely separated points, such as the endpoints of the diameter of the Earth's orbit, for instance.

This is exactly what Bessel did when observing 61 Cygni. Instead of the short distance between his eyes, he chose a much longer distance—the diameter of Earth's orbit (Figure 19.4). Bessel determined the direction to 61 Cygni from E_1, then waited for six months till Earth brought him to the opposite point of the orbit, E_2. From there, he repeated his measurements. The longer base line had paid off indeed: the new direction to 61 Cygni turned out to be different from what it had been when watched from E_1. From the tiny shift in the position of 61 Cygni, Bessel was able to compute its distance. (2)

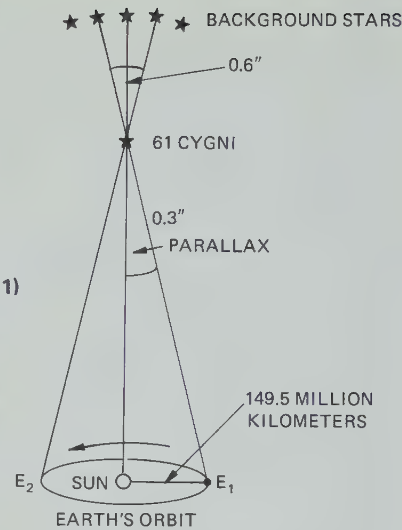


Figure 19.4 Bessel determined the direction of 61 Cygni from two opposite points on Earth's orbit, E_1 and E_2. The difference in direction is about 0.6 second. One half of the difference in direction of a star over six months is commonly known as the parallax of the star. The parallax of 61 Cygni is therefore 0.3 second.

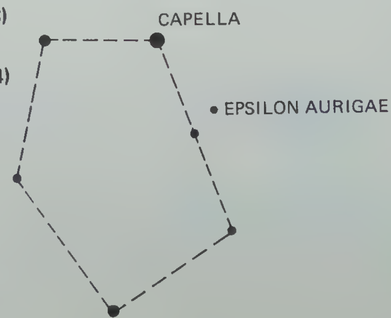
(1) Someone once said that "the parallax to the nearest star must be like an ant running around a dime looking at a street light a mile away".

(2) The distance to 61 Cygni has been found to be 11.1 light-years. Some suggest that it may have a planetary system.

(3) Astronomers have determined that our solar system, from the Sun through the asteroid belt, would fit inside the star Betelgeuse.

Giants and dwarfs. Stars vary greatly in size. Consider Betelgeuse, for instance. It's the first star (other than the Sun) whose diameter was measured. (The diameter was measured by a complicated method we won't go into here.) The diameter of this reddish star is 580 times that of the Sun! (See Figure 19.5.) No wonder astronomers call it a **supergiant** star. (3)

On clear winter nights, you can readily find Epsilon Aurigae, a medium-bright star, in the constellation Auriga the Charioteer. Its diameter of 4 billion kilometers exceeds the Sun's 2700 times! Our entire planetary system except for the orbits of Neptune and Pluto could be comfortably placed within its giant body. (4)



It would be wrong, though, to conclude that all stars are larger than the Sun. Certain very small stars are called **white**

(4) Look at a star chart showing the winter sky and find Betelgeuse in the constellation Orion. Look up the star charts in *Astronomy Without a Telescope*. (ESCP PS-9, Houghton Mifflin, 1971).

dwarfs. One, LP 768-500, is a good example. Having a diameter of about 1500 kilometers, it is smaller than the Moon. Yet it radiates its own light and is clearly visible in photographs of the night sky.

Epsilon Aurigae and LP 768-500 are of course very unusual stars. Most stars lie between these extremes of size. Stars also vary in their masses. While some stars are only one tenth as massive as the Sun, many giants and supergiants contain tens of solar masses.

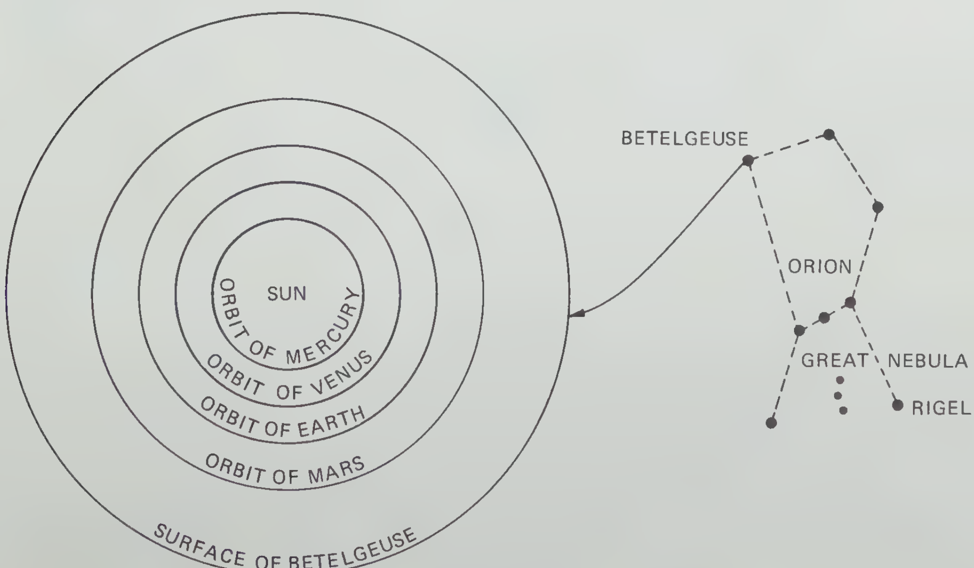
This brings us immediately to the densities of stars. Are supergiants denser than other stars? Again, let us consider Betelgeuse. True, it contains stuff enough to build 20 stars similar to the Sun. But then its volume is so large that 200 million Suns could be easily packed into its giant body. Which of the two stars, do you think, is denser? How many times? (5)

(5) The Sun has 10^7 times the density of Betelgeuse.

The average density of Betelgeuse is roughly 1/10,000 that of the air you breathe. Surprised? So were astronomers when they found out that the mighty supergiant was sort of a cosmic ghost made up of almost empty space.

The story is different when it comes to white dwarfs. Can you imagine a material a thousand times as dense as steel?

Figure 19.5 If Betelgeuse were placed where the Sun is, the four inner planets would find themselves deep inside the hot interior of the supergiant star.



We have nothing like that on Earth. Yet that's the density of many white dwarfs. LP 768-500 is even denser. Gases within its tiny body are compressed to such an extent that a single cubic centimeter of the material would weigh a hundred tons on Earth!

The "countless" stars? If someone asked you, "How many stars are there in the sky?" what would you answer? Several hundred? A thousand? Countless millions?

The number of naked-eye stars seen under good viewing conditions is smaller than many people believe—it's roughly six thousand. Since, however, one half of them are below the horizon, only about 3000 naked-eye stars grace the sky on any clear moonless night.

activity 19.1 How many stars can you see?

Watch the night sky through binoculars. Can you see more stars than with unaided eyes? Do stars appear brighter? Bigger? (1)

(1) Questions in the activity are to alert the students. No formal answers are required.

Find a planet in the sky and observe it carefully. First with unaided eyes, then through binoculars. Does it look larger through binoculars? Are planets actually bigger than stars? Why do binoculars magnify planets but leave the images of stars unaltered?

Select a small area in the sky bounded by three or four bright stars. How many naked-eye stars are there in the area? Count the number of stars you can see with binoculars. How many stars do you see this time? Repeat the observations with a small telescope if one is available.

Once again we observe how limited our eyes are. They reveal only the brighter stars. Having a much greater light-gathering power, binoculars and telescopes detect many, many fainter stars. But a camera attached to a telescope is an even more sensitive device. When exposed to a star-rich region for several hours, a single photographic plate may contain images of tens of thousands of stars.

We shall learn later that the Sun is a member of a huge star island called the Milky Way system. Do you know how

many stars it contains? A hundred billion! Sounds incredible, doesn't it? But look again at Figure 17.2, and remember that the photograph covers only a tiny area of the sky. Moreover, not all the stars appear on the picture. Many are too faint to leave their images on a photoplate, others are hidden by extensive gas and dust clouds found in many parts of the Milky Way system.

The name game. Where did the stars get their names? They don't carry name tags on their surfaces, do they?

The ancient stargazers divided the sky into a number of areas called the **constellations.** All stars within the arbitrarily chosen boundaries of a constellation were said to belong to it. Presently 88 constellations are recognized.

Many constellations were named after characters or objects in ancient mythology. One myth told of Helios, the Sun god, who entrusted his young son, Phaeton, to drive the Sun chariot across the sky. As the horses noticed that the reins were not held by the strong hands of the father, they started galloping. The path of the wild ride is still seen in the sky as the glowing Milky Way, which was formed by sparks struck by the horseshoes. The journey came to a tragic end. The chariot left the road and plunged into the river Eridanus, where the little traveler drowned. Night fell early that day.

When Phaeton's best friend learned of what had happened, he soothed his grief by singing sorrowful songs. They were so moving that the gods turned the little singer into a swan and brought him up to the heavens. And there, as Cygnus the Swan, he continues singing the sad swan song (Figure 19.2). Eridanus, too, is a constellation. It winds its way from the celestial equator toward the south celestial pole. (2)

How do we distinguish between the individual stars of a constellation? Originally names such as Betelgeuse, Arcturus, or Sirius were assigned. But astronomers ran out of names before long. Besides, how would you like to memorize thousands of star names? A better solution was found in designating stars by either Greek letters (α or alpha, β or beta, γ or gamma, δ or delta, ϵ or epsilon, and so on) or numbers followed by a form of the constellation's name. This is why stars have names such as α Orionis (alpha of the constellation Orion; it is also called Betelgeuse) or 61 Cygni (number 61 of the constellation Cygnus). Although the brightest star of each constellation is usually denoted by α, the next brightest by β, the next by γ, and so on, there are many exceptions to this rule. (3)

(2) A good reference source for constellation mythology is *Stars in Our Heaven*, by Peter Lum (Pantheon, New York, 1948).

(3) The number sequence of stars as "61" in Cygnus is commonly referred to as the Flamsteed designation.

activity 19.2 *Comparing brightnesses of stars*

On a clear moonless night, locate the Big Dipper constellation (Figure 19.7), also known as the Great Bear or Ursa Major. Also locate the constellations Leo the Lion and Gemini the Twins. Compare the brightness of α Ursae Majoris to that of β Ursae Majoris. Which of the two stars appears to be brighter? Do the same with α Leonis (Regulus) and β Leonis (Denebola). And which of the twins, Castor or Pollux, do you estimate to be brighter? Are alphas always brighter than betas?

(1)(1) No.

But how about the name of the white dwarf LP 768-500? Doesn't it look more like a credit card number than a name? This star is in the constellation Cetus, and it could be named accordingly. However, astronomers have divided the sky into still smaller areas than the constellations. Instead of using names, astronomers denote them by numbers. It happens that LP 768-500 is the 500th star on the photographic plate taken at Palomar Observatory of the area 768 and that its true nature was revealed by Willem J. Luyten of the University of Minnesota. Does this information help you to understand the meaning of the symbols used in the star's name?

(2)(2) This refers to Luyten-Palomar-768 area and the 500th star.

Traveling along with the Sun. Two centuries ago there lived a colorful English astronomer named Sir William Herschel. Born in Germany and a musician by profession, he went to England at an early age to become one of the "greats" in astronomy of his time. The discovery of the planet Uranus ranks among his most spectacular achievements. But his finding that the Sun moves through space was even more important astronomically.

Comparing present positions of stars with their positions on star maps made in earlier centuries, Herschel noticed two unusual areas in the sky. Within one of them stars appeared to be drifting away from each other, while in the other one they seemed to be coming together. Moreover, the two areas were in exactly the opposite parts of the sky. We observe a similar phenomenon when we travel along a straight stretch of a highway. Remember how trees, telephone poles, and build-

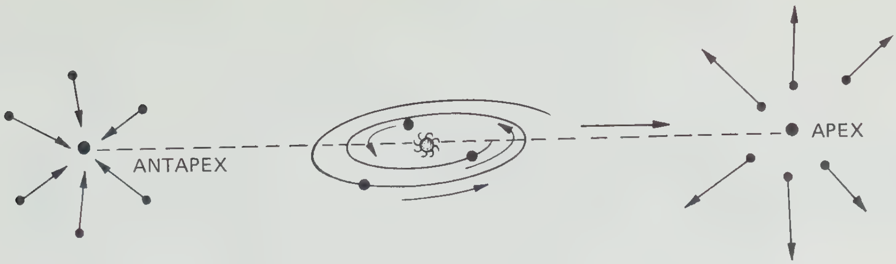


Figure 19.6 Stars appear to be drifting away from the apex, the point toward which the Sun is moving. At the antapex, the opposite point in the sky, the stars appear to be coming together.

ings on both sides of the road seem to drift away from each other as you approach them, and how the highway closes up behind you? It's the perspective! Apparently, the Sun is moving through space. Like a swiftly gliding celestial vehicle, it dashes toward the **apex**, a point in the constellation Hercules, and[3] rushes away from the **antapex**, south of Sirius, the brightest star in the night sky. As it does so, it carries you and me and the entire solar system along (Figure. 19.6).

(3) Solar velocity in relation to the nearby stars is roughly 19.6 km/sec.

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activity 19.3 Locating the apex

Find the bright star Vega (α Lyrae) and the less bright star, α Herculis. Imagine the two stars joined by a straight line. The point on it 3/5 of the way from α Herculis to Vega is the approximate position of the apex.

"Eternal" constellations—or are they? See if you can find an old astronomy book or a star chart published ten or 20 years ago. Compare the shapes of constellations then with their present appearance. Have they changed?

Constellations look tonight exactly as they did a year ago, or even during the horse and buggy days. And we have every reason to believe that they will continue appearing the same way for many centuries to come. No wonder they are said to be "eternal." Yet stars do move. Some cover only a few kilometers per second, others are faster, and still others cover a hundred

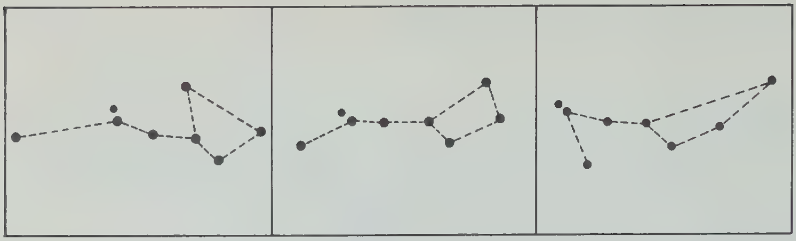

Figure 19.7 These drawings show the Big Dipper as seen by cave men 100,000 years ago (left), as it appears today (center), and as it will appear 100,000 years from now (right).

kilometers in one single second. In fact, most stars dash many times faster than the fastest bullets. Why then do the shapes of constellations remain unchanging for centuries?

Compare the speed of a nearby canoe with that of a speedboat across the lake. Which of the two vehicles appears to be moving faster? And doesn't a flying bumblebee in the back yard of your home describe a wider arc in a second than does a distant jet plane in the sky? Yet you wouldn't bet that the bumblebee flies faster than the jet does, would you? What is it that makes the plane appear to be almost stationary despite its high speed?

Stars are so far away from us that even the best present-day instruments cannot detect their displacements overnight. But astronomers are patient. As they compare photographs of the sky taken many years apart, many stars display small but measurable changes in their positions. The average **annual displacement** of all naked-eye stars is roughly 0.1" (one tenth of a second—much too small to be noticed with unaided eyes. But over a long period of time, the night sky changes consider-

Figure 19.8 These two photographs were taken 22 years apart. In that time, Barnard's star (indicated by the arrow) has moved noticeably. The other stars have not changed their relative positions noticeably.

ably. If a million years from now we were allowed to take another look at the heavens, we would find it hard to believe it's the same sky we are enjoying now (Figure 19.7).

The annual displacement record is held by the otherwise insignificant Barnard's star (Figure 19.8). Invisible to an unaided eye, this runaway star covers 10.3" annually. Although swiftly moving, it is far from being the fastest star in space. Why, then, is its annual displacement so high? Remember what was said about the bumblebee in your back yard and the distant jet plane. Less than six light-years from us, Barnard's star is the fourth nearest star to the Sun.

(1) (1) The annual displacement is also known as the proper motion. It is the annual change in a star's right ascension and declination.

(2) (2) Because of the annual displacement of stars, it is necessary for serious astronomers to relocate stars on charts about every 10 years in order to account for their change in coordinates, no matter how slight.

activity 19.4 *How many degrees in a million years?*

We said that the average annual displacement of naked-eye stars is 0.1". What is that equal to in degrees? (There are 60 seconds in a minute and 60 minutes in a degree.) How many degrees does an average naked-eye star cover in a million years? Do you think such a displacement would be noticeable to an unaided eye?

How long does it take for Barnard's star to cover an arc equal to the apparent diameter of the Moon (0.5°)? A year? Ten years? The answer may surprise you. Yet, if all the stars moved that fast, the night sky would change considerably during our lifetimes.

(3) (3) $\frac{1}{36000}$.

(4) (4) Yes.

(5) (5) Approximately 180 years.

CHECK YOUR FACTS

1. Do we see the stars as they are now, or as they were in the past?
2. From what two points did Bessel measure the parallax of 61 Cygni?
3. Which kind of star is denser—supergiant or white dwarf?
4. Is the alpha star of a constellation always the brightest?
5. In what constellation is the apex located?
6. What is the average annual displacement of naked-eye stars?

(6) (6) **ANSWERS** / Check Your Facts

1. As they were in the past.
2. Opposite points of Earth's orbit (6 months apart).
3. White dwarf.
4. Not necessarily.
5. Hercules.
6. 0.1".

READING THE MESSAGE OF STARLIGHT

Do changes in a star's position in the sky tell the whole story about stellar motion? Try imagining a star that dashes like a bullet through space, yet does not shift its position in the sky.

A star moving directly towards or away from us would behave this way. Such a motion is called **radial motion**. Astronomers measure it in kilometers per second. (How is the annual displacement of a star measured?)

As a rule, stars travel obliquely to our line of sight and thus take part in two motions simultaneously: they not only approach or recede (move away) from us, but at the same time change their positions in the sky.

But how can we measure radial velocity, if it takes place along our line of sight? To understand the answer, let's shift our attention back to a scene on Earth.

(1) (1) If you know a star's annual displacement, radial velocity, and the distance from the Sun, its combined speed relative to the Sun can be calculated. This speed is called the space velocity of the star.

Coming or going? Ask the spectrum. You are standing at a railroad station. A train is approaching. The engineer sounds a warning whistle. At the very instant the engine passes you, the pitch of the whistle lowers markedly. What causes it? The noise of the train? A mechanical defect in the whistle? Or has it something to do with the motion of the engine?

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activity 19.5 Swinging the tuning fork

Set a high-pitched tuning fork into vibration and swing it rapidly toward and away from your ear. Do you notice any variation in the pitch?

Mention two more instances where you have observed a similar phenomenon due to motion.

The sensation of sound is produced when sound waves in the atmosphere strike our eardrums. The number of waves our ears receive per second determines the pitch of the sound. The greater the number of waves, the higher the pitch.

Imagine yourself listening to a tuning fork that vibrates 30 times per second. If the distance between you and the tun-

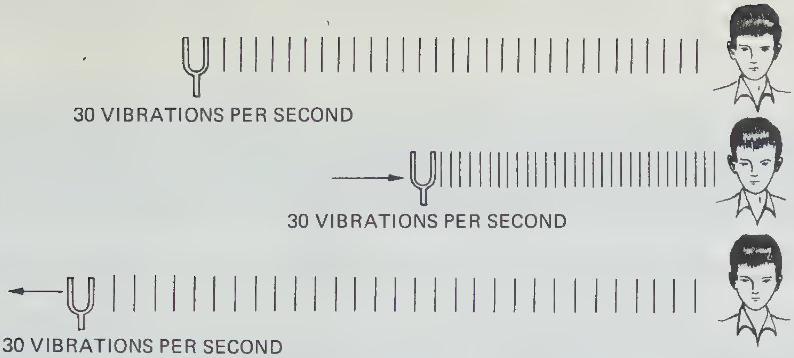


Figure 19.9 In the top drawing, the distance between you and the tuning fork does not change and you hear a "normal" pitch. In the middle drawing, the tuning fork is approaching you and you hear a higher pitch. If the tuning fork is moving away from you (bottom drawing), you hear a lower pitch.

ing fork remains constant, your ears receive 30 vibrations per second and you hear a certain pitch (Figure 19.9). But the story is different when the vibrating fork starts approaching you. The 30 waves are now squeezed into a shorter distance. You receive more than 30 vibrations per second and the pitch becomes higher. Just the opposite happens when the distance increases. The vibrations are now spread over a greater distance, the waves become longer, and the pitch lowers. Would you expect the change to depend on how fast the source moves toward or away from you? Would a higher speed result in a greater change? Or would it be the other way around?

More than a century ago, Christian Doppler of Austria explored the relation between the speed and pitch mathematically. Since then, the phenomenon has become known as the **Doppler effect.**

But what have engine whistles or tuning forks to do with radial velocities of stars? Stars do not emit sounds audible on Earth, do they? But stars radiate light. Like sound, light is a kind of wave or vibration. Just as the pitch of a sound depends on its wavelengths, the color of light is determined by the length of the light waves that enter our eyes.

When light leaves the surface of a star, it contains all the wavelengths of the visible spectrum. But as it passes through the atmosphere of the star, it loses some wavelengths. The missing waves make their absence known by leaving dark lines in the star's spectrum.

This is not surprising. We encountered a similar phenomenon when discussing the solar spectrum. But what makes it different this time is that the dark lines do not appear at their regular positions. In the spectra of some stars, they are displaced toward the red end of the spectrum. Astronomers call this a **red shift.** In other spectra the dark lines are displaced toward the violet end, where the shorter waves are found. What causes the shifting of the lines? To answer the question,

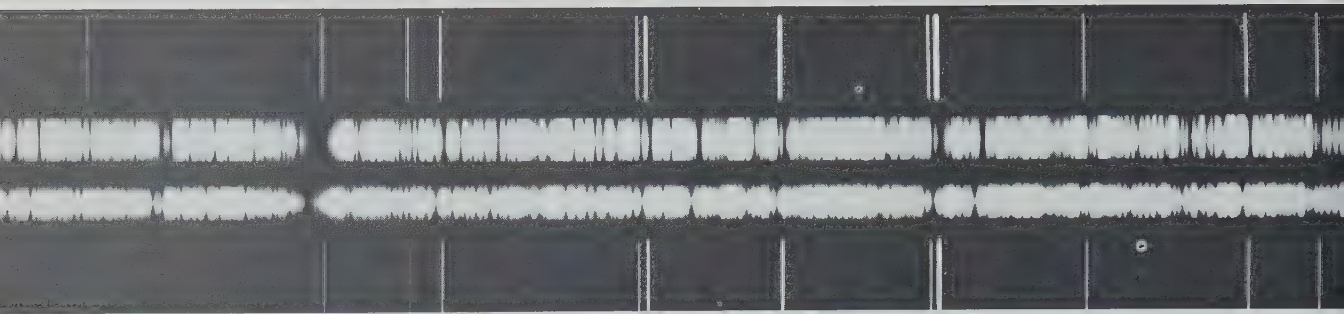


Figure 19.10 The bright-line spectrum at the top and bottom of this photograph is obtained in a laboratory and is used for reference. Compare the bright lines to the corresponding dark lines in the two spectra of the star Arcturus shown in the middle. Notice that the two spectra show shifts in opposite directions. One is a red shift and one is a blue shift. The blue shift occurs when Earth, in its orbit around the Sun, approaches Arcturus. The red shift occurs six months later, when Earth is drawing away from Arcturus. (The two spectra were obtained six months apart.)

remember what happened to sound waves as the tuning fork was swung rapidly toward and away from your ear. Radial motions of stars affect light waves similarly.

As a star recedes from Earth, it stretches its own light waves over a greater distance and thus makes them longer. When the altered waves pass through the spectroscope, these spectral lines shift toward the red end, where the longer waves belong.

Whenever astronomers observe a red shift in a star's spectrum, they know that the star is receding from Earth. The greater the shift, the higher the speed of recession. (1)

A similar reasoning explains why spectral lines of an approaching star undergo a "blue shift"—a displacement toward the violet end of the spectrum. Again, the greater the radial velocity of the star, the greater the shift (Figure 19.10).

Can you think of a star whose spectral lines display no shift at all? (2)

When one star is two. In 1650, an Italian astronomer named Riccioli was rambling through the night sky with his telescope. Suddenly his attention was caught by Mizar, the middle star in the handle of the Big Dipper. Mizar was not alone; there were two stars close to each other! Could the two stars be related—even revolving around each other?

The problem was solved by William Herschel. Using powerful telescopes, he discovered more than 800 similar stars that are really two or more stars. He proved that these **binary stars** or **multiple stars** indeed move around one another in regular orbits. In some cases, we can actually see the stars criss-cross back and forth as they revolve around each other. In other cases, we must study their combined spectra. As voices in a darkened room tell us how many people are talking,

(1) The radial velocity (v) of a star is equal to the change in wavelength due to the star's motion ($\Delta\lambda$) divided by the laboratory wavelength of the same line (λ) times the velocity of light (c): 3×10^5 km/sec.

(2) Such a star has no radial velocity, only annual displacement.

the shiftings of the dark lines in the spectrum of a multiple star disclose how many individual stars are actually present.

How long does it take for the partners of a binary star to revolve around each other? As long as thousands of years, or as short as an hour! It depends primarily on the distance between the two stars. The greater the distance, the longer the time for one revolution.

(3) (3) There are different categories of binary stars. Those that appear double with the naked eye, those that are telescopically separable, and those only separable spectrographically.

It is estimated that at least half of all stars are binary or multiple stars. We are lucky that the Sun is a lonely single star. How would it affect our lives if the Sun acquired a companion?

Binary stars are among an astronomer's best friends. They are talkative about secrets that single stars would have never revealed. Among other things, they tell how much matter their bodies contain and why some stars are more luminous than others. The size of the orbit and the period of revolution are mathematically related to the total mass of the two stars. As soon as the size of the orbit and the period of revolution are determined by observation, the combined mass of the binary can be calculated.

Brightness—real and apparent. An electric bulb may blind you for a while when held close to your eyes, but place it a kilometer away, and it becomes hardly, if at all, visible. A similar property holds for stars as well.

We have seen that a typical star emits roughly as much light as the Sun, but that the star looks so much fainter because it is very far away. The real brightness of a star, or the amount of light it emits per second, is called the star's **luminosity**. It is a property of the star itself and has nothing to do with how far the star is from us. The **apparent brightness**, or the amount of light we receive from a star per second, depends on both the star's luminosity and our distance from the star.

The more wood you add to a campfire, the more heat and light it produces. Do stars behave in a somewhat similar manner? Are the massive stars more luminous than the "skinny" ones? Questions of this kind crossed the minds of many astronomers a few decades ago. Sir Arthur S. Eddington, an Englishman, was one of them.

Using physics and a great deal of mathematics, Eddington concluded theoretically that the more massive stars, indeed, must be more luminous. To verify his reasoning, he selected binaries for which the masses and luminosities of the part-

ners were known, then plotted them in a diagram similar to that shown in Figure 19.11. Observe that stellar masses are placed on the horizontal axis, the luminosities on the vertical axis. In both cases, the solar values are chosen as units: solar mass = 1, solar luminosity = 1.

activity 19.6 The mass–luminosity relationship

Find the least massive star in Figure 19.11. What fraction of the solar mass does it contain? (1) How much mass is there in the most massive star of the diagram? (2)

Estimate the luminosity of the least massive star in the diagram. Then find the most luminous star. How many times more luminous is it than the Sun? (3)

Find the Sun's position in the diagram. How much mass does a star contain if its luminosity exceeds that of the Sun 10 times? (4) 100 times? (5) 1,000,000 times? (6) Estimate the mass of a star which is only 1/10 as luminous as the Sun. (7)

(1) $\frac{1}{7}$.

(2) 50.

(3) One million.

(4) About 1.5 solar masses.

(5) About 2.5 solar masses.

(6) About 50 solar masses.

(7) About 3/5 solar mass.

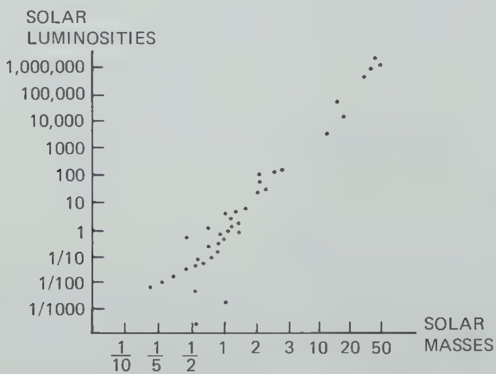


Figure 19.11 As soon as a star's luminosity is known, its mass can be found from this diagram.

Are stars spread evenly across the entire diagram? (8) Do you notice any regularity in their arrangements? Describe it. Can you deduce any relation between the mass of a star and its luminosity? Express it in words. (9) Do your findings agree with Eddington's conclusion? (10)

If stars were distributed evenly across the diagram, would you be justified in saying that the more massive stars are also

(8) No.

(9) The more mass a star contains, the more luminous it is.

(10) Yes.

more luminous? Or would it be proper to say that most massive stars are the least luminous? What kind of a relation between stellar masses and luminosities could you deduce from such a diagram?

Take another look at the diagram. Do all stars obey the mass–luminosity relation? Where are the "dissenters," if any, located? How big are their masses and luminosities? Any idea of what kind of stars they might be?

You just observed that stars form an orderly ascending band rather than a chaotic mishmash of points in the diagram. But several exceptions are known.

Most of the stars that don't obey the mass–luminosity relation are located in the lower left corner of the diagram. Can you guess what they are? All white dwarfs! But their behavior is understandable. So different are white dwarfs from all other stars that their compliance with the mass–luminosity relation would have been a sheer miracle.

The mass–luminosity relation was developed using binaries. But how about single stars? Do they follow the same rules of the game? The answer appears to be yes. Stars of binary systems are not different from the single members of the stellar community. We can find all kinds of stars—normal, giants, supergiants, even white dwarfs—among both groups of stars. The brighter companion of Alpha Centauri, for instance, looks very much like a married twin sister of our own Sun, so similar the two stars are. It is estimated that roughly 90 percent of all the stars honor the mass–luminosity relation. Among the best known nonconformists are the already mentioned white dwarfs and a number of other stars undergoing important changes in their stellar careers.

Color→ temperature→ luminosity→ mass. About a decade before Eddington suggested the mass–luminosity relation, two other astronomers—Ejnar Hertzsprung of Denmark and H. N. Russell of the United States—had a different idea. Is there a relation, they wondered, between a star's spectrum and its luminosity?

It was known already in those days that stars have different spectra. In some, helium lines are prominent; in others, hydrogen or metallic lines stand out. To speak intelligently about the various spectra, astronomers divided them into a number of spectral types. The most frequently encountered

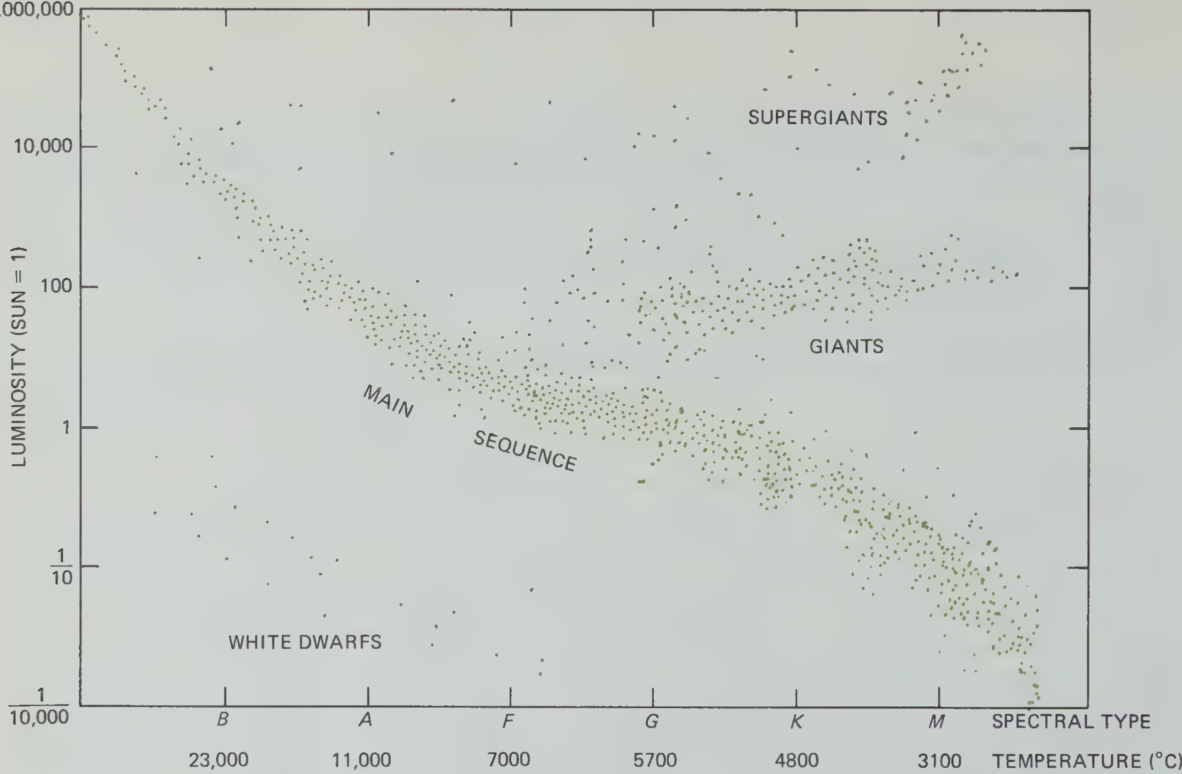


Figure 19.12 In this diagram of stars around us (called a Hertzsprung-Russell diagram), each dot represents a star.

types were denoted by the letters B, A, F, G, K, and M. The(1) spectral types turned out to be closely associated with the colors of stars as well. B stars, for instance, are blue, G stars are yellow, and M stars are red. But colors, you remember, tell us the surface temperatures of stars. Stellar spectra, therefore, can be likened to superthermometers that enable astronomers to measure temperatures over cosmic distances.

(1) One way to help you remember spectral sequence is the mnemonic expression, Be A Fine Girl, Kiss Me. This also shows the range of color from blue to red.

This was known to Hertzsprung and Russell in the early 1910s. But they suspected that stellar spectra may carry news about the luminosities of stars as well. To investigate the problem, they selected a number of stars whose spectral types and luminosities were known, then plotted them in a diagram similar to that in Figure 19.12. On the horizontal axis they placed the spectral types; the vertical axis was reserved for stellar luminosities. Again, the luminosity of the Sun was chosen for the unit (luminosity of the Sun = 1).

The result was astonishing. About 90 percent of all the stars had arranged themselves neatly along a narrow band known as the **main sequence**. It stretches across the diagram from its upper left corner (high temperature and high luminosity) down to the lower right corner (low temperature and low luminosity). The looked-for relation was established! Can you express it in words?

True, a number of stars can be found off the main sequence. But they are exceptions. They are either developing stars that have not yet reached the main sequence where the stable stars belong, or else they are aging stars undergoing the last stages of their lives.

activity 19.7 *The Hertzsprung–Russell diagram*

Examine the main sequence. Which stars are the most luminous? Which are the least luminous? (2) (3)

Find the position of the Sun on the main sequence. What spectral type does it belong to? What are its color and surface temperature? Sirius, another main sequence member, is an A star. Where is its position on the main sequence? What color does it have? What surface temperature? How many times more luminous is it than the Sun? (4) (5)

If a star is only $\frac{1}{100}$ as luminous as the Sun, what spectral type does it belong to? What is the star's color? Its surface temperature? (6)

If you went for a long trip through space, what spectral type stars would you encounter most frequently? Which least frequently? Would you probably meet stars similar to the Sun? Justify your statements. (7)

Are there any M stars that do not belong to the main sequence? Where are they located? Are they more or less luminous than the M stars of the main sequence? How could you account for the luminosity difference? (Remember why a match radiates less light than a pile of burning wood.) Can you now explain why the G, K, and M stars from above the main sequence are called giants? And those still higher in the diagram the supergiants? (8) (9)

Turn now to B and A stars of the main sequence. Where else in the diagram do you find stars of the same spectral types? Are they as luminous as their blue and blue-white counterparts on the main sequence? How many of them would you need to get as much light as you receive from the Sun? How is it possible for an immensely hot B or A star to have this low a luminosity? What do we call these stars? (10) (11)

Consider the blue main sequence stars, red supergiants, and the white dwarfs. Which of the three kinds of stars have the hottest surfaces, the highest luminosity, the greatest density? (12)

(2) B type.

(3) M type.

(4) G; yellow; 5600° C.

(5) Between B and F; blue-white; 11,000° C; about 20 times.

(6) M; red; 3100° C.

(7) M most frequently because they are the most common stars. (They do not appear to be the most common on the H-R diagram because the diagram shows the abundances of the various types of stars as seen from Earth. Since red stars are faint, only the nearby ones are seen.)

(8) Yes, above the main sequence in the upper right corner. More luminous because their light-radiating surfaces are much larger.

(9) Red giants are much larger than red main-sequence stars. Red supergiants are still larger.

(10) Lower left corner. Less luminous. About 20 or more.

(11) They are much smaller than their main sequence counterparts. White dwarfs.

(12) Blue main-sequence stars. Red supergiants. White dwarfs.

We conclude that the nearby stars can be divided into three distinct groups. The overwhelming majority of them are on the main sequence. These are the stars we referred to earlier as the "normal" stars. The rest of the stellar community is made up of nonconformists which violate the temperature-luminosity rule in one way or another. The upper right corner of the diagram is the playground of the largest stars known—giants and supergiants; the lower left corner is the basement quarters of the slowly dying white dwarfs. (1)

(1) Have students look up the spectral types and the luminosities for several other familiar stars and see where they fit on the HR diagram.

But the main sequence teaches us something else. In the preceding section we learned that stars with greater masses are more luminous. Where are the most luminous main-sequence stars located? What can be said about their masses? The blue B stars are among the "fattest" members of the sequence, about ten times as massive as the Sun. As you descend the HR sloping main sequence, you meet cooler, less luminous, and less massive stars. At the very bottom of the sequence, you reach the land of midgets. Small and cool, the dull red M stars are among the "skinniest" members of the stellar population. They contain only one tenth of the mass the Sun does.

Do you see now how the basic properties of a star are interrelated? It is the mass that determines the luminosity, the spectral type, the color, and the surface temperature of the star. You cannot take a ball of gas and say, "I want you to turn into a green star with red polka dots on your surface, temperature 100°C, luminosity unexcelled." Nature does not build stars by our specifications. It has its own laws and standards. We can recognize and sometimes use them, but we cannot alter them.

Pulsating giants—lighthouses of the universe. In 1784, John Goodricke of England came across a peculiar star. Within less than two days, it brightened to almost double its minimum light, then returned slowly to the regular brightness, only to start another identical cycle immediately. The fluctuation repeated itself without cessation. The name of the star was Delta Cephei, its period—5 days and 9 hours. (2)

(2) Have your students look on a star chart for the constellation Cepheus and see if they can find the delta star. This is the prototype for all cepheid variables.

What kind of an object is it? A binary having a dark companion that eclipses it periodically, or a blinking distant star trying to send us some kind of a message? Goodricke never unraveled the secret. But present-day spectroscopists tell us that Delta Cephei cannot be an eclipsing binary, as its light comes from a single source. Instead, they say, it is a pulsating giant that expands and contracts rhythmically. As it does so,

it changes its energy output. Today hundreds of similar stars have been recorded.

Astronomers distinguish between several groups of pulsating stars. Two of them—the **RR Lyrae variables** and the **cepheids**—have turned out to be invaluable in measuring distances to remote celestial objects, such as star clusters and galaxies. In fact, it was by means of pulsating variables that the existence of other galaxies was revealed. But more about that later.

The RR Lyrae variables were named for RR Lyrae, a typical representative of this group. Blue-white giants about 50 times more luminous than the Sun, they pulsate in periods ranging from 6 hours to one day. The remarkable thing about the RR Lyrae variables is that their luminosities are almost equal. True, some appear brighter and others fainter depending on their distances from Earth, but the rate of their energy output varies little from star to star. In this respect, they can be likened to identical electric bulbs placed at various distances from an observer. Knowing the star's luminosity (which is 50 times greater than that of the Sun) and its brightness (which can be measured), the distance to the star can be found readily. But the real value of RR Lyrae variables goes far beyond that.

We learned earlier that stars like togetherness. Many of them are members of binary or multiple systems. But once in a while, much larger congregations are encountered. Particularly impressive among them are the globular clusters (Figure 19.13). Between 20,000 and 300,000 light-years from Earth, they rank among the most remote members of the Milky Way system. Do you know how their distances were measured? By means of RR Lyrae variables! Globular clusters contain nu-

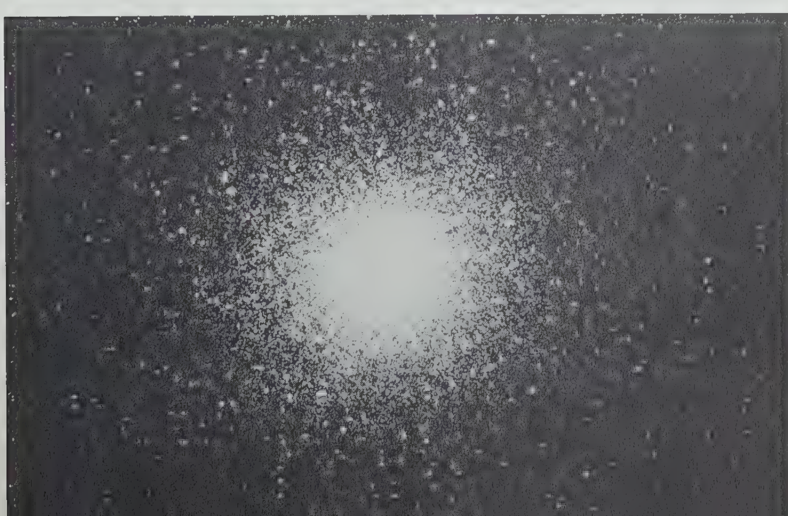


Figure 19.13 This globular cluster is estimated to contain 500,000 stars. A dazzling view would appear before your eyes if you watched the sky from the center of this cluster. Probably as many as 100,000 stars could be seen, some shining as brightly as the full Moon in our sky.

merous stars of this kind. As soon as the distance to one of them is fixed, the approximate distance to the cluster itself is known.

But cepheids are even more valuable in charting the universe. (Their name is derived from Delta Cephei, the first star of this kind discovered.) A thousand to ten thousand times as luminous as the Sun, these yellow supergiants can be seen millions of light-years away. Their pulsation periods range from one day to several weeks, but in most cases they are in the neighborhood of 5 or 6 days.

Can cepheids, like RR Lyrae variables, be used in distance measuring? At first the answer seems to be no. Unlike RR Lyrae variables, whose luminosities are equal, cepheids display a wide range in their energy output. But the situation changed when Harlow Shapley, an American astronomer, discovered that periods and luminosities of cepheids are closely related: the longer the period, the greater the luminosity! Moreover, he derived a diagram that enables astronomers to find the luminosity of a cepheid as soon as its period of pulsation is known. A star's luminosity and brightness is all we need to figure out its distance. (1)

Cepheids are among the most luminous stars in the universe. They cast their light through almost unbelievable distances. A number of them have been identified even in other galaxies, far beyond the confines of our Milky Way system. They can be likened to remote lighthouses in space. By figuring out their distances, astronomers learn a good deal about the structure of the universe and our own position in it. (2)

(1) Emphasize the importance of both RR Lyrae stars and cepheid variables for determining distances to deep space.

(2) Refer to visual aids showing photos of globular clusters; RR Lyrae variables are often associated with globular clusters. RR Lyrae variables are sometimes referred to as cluster variables.

CHECK YOUR FACTS (3)

1. What determines the pitch of sound?

2. What happens to the pitch when a sound source approaches you?

3. How can we tell from the spectrum of a star whether the star is approaching us or receding from us?

4. About what percentage of all stars is estimated to be binary stars or multiple stars?

5. What is the relationship between the mass and the luminosity of a star?

6. In what part of the Hertzsprung–Russell diagram are most stars located?

7. What are RR Lyrae variables used for in astronomy?

(3) **ANSWERS** / Check Your Facts

1. Frequency.
2. Pitch rises.
3. Approaching star shows a spectral blue shift, receding star shows a spectral red shift.
4. 50%.
5. Mass is proportional to luminosity; the greater the mass, the more luminosity.
6. The main sequence.
7. To determine distances.

NOVAS AND OTHER UNUSUAL OBJECTS

When a star blows its top. In 134 B.C., a bright star appeared in the constellation Scorpion, reached quickly a maximum brightness, then faded away, to eventually disappear from view. It has never returned since.

The unusual celestial show was watched by many people including Hipparchus, a prominent astronomer of the time. He described it later as a new star, "different from all others previously seen, one born during my own age."

The great Greek was wrong this time; the brilliant object was not born during his life. Too faint to be seen with a naked eye, the star had been in the sky long before the outburst took place. Stars that suddenly increase many times in brightness are called **novas**. (4)

(4) Some novas have been known to fluctuate their brightness many times. Nova Puppis in 1942 fluctuated 2000 times in only 100 days.

About 50 novas are estimated to appear in the Milky Way system annually, but seldom do they get bright enough to be seen with an unaided eye.

A star does not change basically during the nova stage. True, it ejects about $\frac{1}{10,000}$ of its mass, but that, relatively speaking, is not much. Your body loses more than $\frac{1}{10,000}$ of its mass during one single class period, yet the loss does not alter you fundamentally. And so it is with novas. A nova eruption can be likened to a slight skin irritation that may be annoying for a while but leaves the body unaltered when the skin has healed.

The cause of a nova outburst is not known. Recently astronomers have become intrigued by the fact that many, if not all, novas seem to be members of very close binary systems. There is a possibility, argue some astronomers, that the mutual gravitational forces raise so great a tide in the less dense partner that its gases start flowing into the nova star. When the latter has sucked in more mass than it can safely accommodate, the star blows off its surface. This also could explain why some novas undergo irregular eruptions every few decades.

Supernova explosions. Though spectacular, nova outbursts can be likened to innocent firecrackers when compared to **supernova** explosions. Stars undergoing this kind of (5) a tragedy cease to exist as the celestial bodies they were before. When the great show is over, all that remains of the once lively star is a dwarf of a fantastically high density surrounded by a rapidly expanding gas cloud called a **nebula**.

(5) The brightness of these may change hundreds of millions of times.

Supernovas are the producers of the heavy elements. It is in their highly compressed and hot interiors that atoms of

Figure 19.14 The rapidly expanding Crab nebula is believed to be the remains of the "guest star" seen by Chinese stargazers in 1054.

nickel, gold, platinum, and other heavy elements come into being. The gold pin on your dress or lapel was made of stuff that was born in supernovas long before Earth and the Sun appeared on the scene. Guess how these metals happened to be on Earth.

Supernovas are rare. Only three supernovas have been observed with the naked eye in the Milky Way system during the past thousand years. About 200 have been spotted on photographs of other galaxies. Of course the actual number may be considerably greater, as large parts of the sky are hidden by extensive gas and dust clouds. (1)

During its peak luminosity, an average supernova out- (2) shines the Sun about 100 million times, although some have been brighter than the entire galaxy to which they belong. Think of what would happen to us if the Sun turned into a supernova. Fortunately, it does not have enough material to do that kind of fireworks. The yellow and red supergiants and the luminous blue main-sequence stars are much more probable candidates for a supernova explosion.

One of the most striking supernovas ever observed appeared in Andromeda Spiral back in 1885. When at maximum luminosity, this brilliant object released more light in one short day than our Sun does in a million years! (3)

One of the three supernovas seen in the Milky Way system in the past thousand years is closely associated with the rap- (4) idly expanding Crab Nebula (Figure 19.14) in the constellation Taurus the Bull. The fact that the nebula's diameter increases

(1) Assign your students to find the characteristics of several of the interesting nebulas.

(2) A series of excellent photographs and slides of nebulas and other deep-sky objects are available from the Hale Observatories through the Cal Tech bookstore in Pasadena.

(3) If possible, show the EBF filmstrip on nebulas in "Scanning the Universe" Series and the Life filmstrip called "The Starry Universe."

(4) Some people have suggested that the star of Bethlehem, the star which guided the Wise Men, could perhaps have been a nova or supernova. There is, however, no record of any bright nova seen at the time of the birth of Christ.

more than 2700 kilometers every *second* (the distance from Minneapolis, Minnesota, to Miami, Florida!) suggests that the nebula might have come into existence in a supernova explosion. Knowing the size of the Crab and the rate of its expansion, we can estimate the time of the blast. Do you know when it happened? Nine centuries ago! But ancient Chinese records tell of a bright "guest star" in Taurus that visited their skies in the summer of 1054. Add the 900 years, and you get 1954! That's pretty close to now, isn't it? There seems to be no doubt that the Crab Nebula and the Chinese "guest star" are the same object, observed nine centuries apart.

What happens to a star during a supernova explosion? Does part of it survive the blast? The answer is closely related to some of the most recent discoveries of our present-day astronomy—neutron stars, pulsars, and black holes. They are discussed in the next section.

Neutron stars, pulsars, and black holes. Just before a star several times more massive than the Sun exhausts all its energy supply, it collapses under its own weight. Gravitation crushes it into a volume that is tiny compared to its original size. When the matter within the star becomes squeezed so tight that the nuclei and electrons of the star's matter begin to touch each other, the star stops shrinking. The compressed star, coiled like a gigantic spring, rebounds in a violent explosion—the supernova. Half the stellar matter is flung into space to become a rapidly expanding nebula. Within the remaining core, the electrons are crushed into the nuclei of their atoms. The remnant of the star is now a ball of electrically neutral particles called neutrons. For this reason it is called a **neutron star**.

(5) (5) If all the material of Earth were packed to such density, the entire Earth would fit into a classroom. The diameter of the average neutron star is only 10-15 km.

Neutron stars were first discovered by radio astronomy, the study of the radio waves emitted by stars. Radio astronomers came across points in the sky from which rapid bursts of radio energy were originating. The bursts, or pulses, were repeated with amazing regularity at intervals ranging from $\frac{1}{30}$ of a second to several seconds. Quickly named **pulsars**, the new radio sources were a real mystery. Some people even suggested that they were signals from little green men in a distant planetary system! As it now turns out, the blinking pulsars are actually neutron stars rapidly spinning on their axes. The energy we receive from them appears to be coming from particularly active spots on their surfaces. As the stars rotate, energy "beacons" emitted by the spots sweep through

(6) (6) One of the mysterious pulsars has been found associated with the Crab Nebula. There may be a connection between the two.

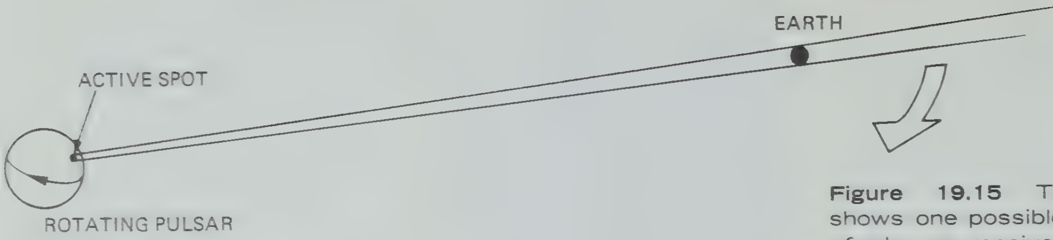


Figure 19.15 This diagram shows one possible explanation of why we receive energy from pulsars in bursts rather than steadily. We receive a burst each time the energy beacon sweeps across us.

space much like the light of distant lighthouses. If Earth happens to be in a beacon's path, radio bursts and flickering light are observed (Figure 19.15).

Astronomers have recently suspected that there are probably even stranger things in the universe than neutron stars. Under special circumstances, a collapsing star zooms right past the neutron star stage and continues shrinking forever. When the former star reaches a diameter of about three kilometers, very strange things begin to happen. Gravitation becomes so strong that even light cannot escape from the surface. The superdense collapsing object has turned into an invisible ghost. Astronomers call this strange ending of a star a **black hole**.

CHECK YOUR FACTS

1. Were are heavy elements produced?

2. How many supernovas have been observed in the solar system with the naked eye in the last thousand years?

3. What happens to a star after a supernova explosion?

(1)(1) **ANSWERS** / Check Your Facts

1. In supernovas.
2. Three.
3. The remnant of the star collapses to form a small dense object such as a neutron star.

THE BIRTH AND DEATH OF STARS

Contrary to what most people think, the space between the stars is not empty. On the average, the interstellar space contains one atom per cubic centimeter. This is a very low density, much closer to being "nothing" than the best vacuum we can obtain on Earth. The matter between the stars is not distributed uniformly; in some places it is clumped together to form great nebulas. Some nebulas reveal their presence by blocking out the stars that lie behind them; we see them as

dark patches in rich star fields. Other nebulas reflect starlight, and still others emit their own light and thus appear as glowing bright regions in the sky (Figure 19.1).

It is in these huge clouds of gas and dust that stars are born. The star begins to form when a clump of gas and dust develops within a nebula. Contracting under its own gravitational pull, the clump turns increasingly smaller in size, denser, and hotter. Eventually it begins glowing dull red. As the temperature continues rising, the emerging star becomes hot enough at its core to trigger nuclear reactions. Hydrogen —the most abundant element in stars—is now being converted to helium. For a while the star draws its energy from both contraction and nuclear reactions. But when it gets even hotter, the contraction stops. The nuclear powerplant is now the only supplier of energy. This marks the star's arrival on the main sequence of normal stars. The carefree days of childhood are over; the star has entered the adult stage.

How long do stars stay "normal," that is, on the main sequence? The answer depends on the mass. You would guess that the larger the mass, the greater the energy supply, and the longer the lifetime of a star. It is true that the more massive a star, the greater its supply of nuclear energy. But massive stars are much more luminous, and they use up their energy at a much quicker rate than less massive stars. As a result, large blue and white stars have shorter lifetimes than small red stars. Take Sirius as an example. It has three times the mass of the Sun but is more than twenty times as luminous. While the Sun will last for about ten billion years, reckless Sirius will burn out in only one billion years. Who would have guessed that the adult life of massive Sirius will be so much shorter than the Sun's life? Sirius will pay dearly for its extravagance.

What happens to a star after it leaves the main sequence? Astronomers believe that the stellar core, depleted of hydrogen, collapses under its own gravitational force. The tremendous heat brought about by the collapse triggers nuclear reactions outside the core. This makes the star expand—at first slowly, then faster and faster. The massive blue and white stars turn into supergiants, and probably undergo a spectacular supernova blast. Smaller stars, such as the Sun, become red giants before collapsing to tiny and incredibly dense white dwarfs. During the next twenty to thirty billion years, the white dwarfs turn into lightless chunks of matter bearing no resemblance to the glowing celestial powerhouses of the

main sequence. It is an amazing discovery of modern astronomy that even the "eternal" stars go through the cycle of birth and death that is the rule on our own Earth.(1)

(1) "The Starry Universe," the Life filmstrip, has a section of excellent illustrations showing the sequences of stellar evolution.

CHECK YOUR FACTS(2)

(2) **ANSWERS** / Check Your Facts

1. One atom per cubic centimeter.
2. In nebulas.
3. This depends on the star's mass. The more massive it is, the shorter the time that it stays in the main sequence. For example, Sirius will remain 1 billion years, the sun 10 billion years.

1. On the average, how many atoms are there in each cubic centimeter of interstellar space?

2. Where are stars born?

3. How long do stars remain on the main sequence?

APPLYING WHAT YOU HAVE LEARNED(3)

(3) **ANSWERS** / Applying What You Have Learned

1. No; no.
2. No; no.
3. Yes.
4. No.
5. No; yes.
6. The blue.
7. The eclipsing binary will display two sets of dark lines.
8. The Crab is an expanding nebula left over from a supernova explosion. The nebula in Orion is not expanding.
9. About 3,000.
10. Lyra. No.
11. (a) Chemical composition of atmosphere, (b) radial velocity, (c) spectral type.
12. No. See pages 396, 397, 401, and 402.

1. Are all the stars of a constellation the same distance from Earth? Will they stay together forever?

2. Were stars of a constellation born simultaneously? Will they die together?

3. Can a star switch from one constellation to another?

4. Is the Sun a member of some constellation?

5. Would the constellations look different from Mars than they do from Earth? Would they look different from the neighborhood of Betelgeuse?

6. If two main-sequence stars—one blue, one red—are equally bright, which of the two is farther from Earth?

7. How can astronomers tell the difference between an eclipsing binary and a pulsating variable?

8. What is the difference between the Crab Nebula and the Great Nebula in Orion?

9. Suppose a friend tells you how much he enjoys watching the countless stars from his back yard. You ask him if he has a telescope. "No," he replies, "but I have good eyes." How large is the number he refers to as "countless"?

10. Which constellation is RR Lyrae in? Are all the RR Lyrae variables in the constellation Lyra?

11. Mention three properties of a star that can be determined by examining its spectrum.

12. Do the light fluctuations of pulsating variables and pulsars arise from the same cause? Explain your answer.

13. What is the difference between the luminosity and the brightness of a star? Can a red main-sequence star be very luminous? Can a blue main-sequence star be faint?

14. In 1885, an exceptionally bright supernova appeared in Andromeda Spiral, which is 2 million light-years away. When did the explosion actually take place?

KEY WORDS

light-year (p. 378)
parallax (p. 380)
supergiant (p. 380)
white dwarf (p. 380)
constellation (p. 383)
apex (p. 385)
antapex (p. 385)
annual displacement (p. 386)
radial motion (p. 388)
Doppler effect (p. 389)
red shift (p. 389)
binary star (p. 390)
multiple star (p. 390)
luminosity (p. 391)
apparent brightness (p. 391)
main sequence (p. 394)
RR Lyrae variable (p. 397)
cepheid (p. 397)
nova (p. 399)
supernova (p. 399)
nebula (p. 399)
neutron star (p. 401)
pulsar (p. 401)
black hole (p. 402)

Figure 20.1 To take this photograph of galaxy M 33, which is 2 million light-years away, an exposure time of 8½ hours was needed!

Introductory Demonstration

You will need two large balloons, ink (Magic Marker), cotton balls, and glue. Blow up one balloon part way and draw spots of ink on it. Now, blow it all the way up. Ask your students for observations. Blow up the second balloon part way, then carefully glue cotton all around it. Blow the second balloon up all the way. Ask students for comments. You can relate this to the expanding universe and the steady-state theories. The demonstration will initiate interest, curiosity, and discussion.

chapter 20

Our Galaxy and Other Star Islands

WHAT IS THE MILKY WAY SYSTEM LIKE?

More than two centuries ago, Herschel realized that the Sun is a member of a large gathering of stars. But how big is this star system? What is it like? Has it the shape of a basketball? Or is it more like a pumpkin, a hamburger, a hot dog, or what?

The Milky Way—what is it like? For a long time astronomers had no answers to these questions. But then they began to study that narrow, luminous band that arches across the sky—the Milky Way. (1)

(1) See the EBF filmstrip "The Milky Way and Other Galaxies," from *Scanning the Universe* Series.

What is the Milky Way? Photographs reveal that it is made up of nebulas and countless stars, most of them much

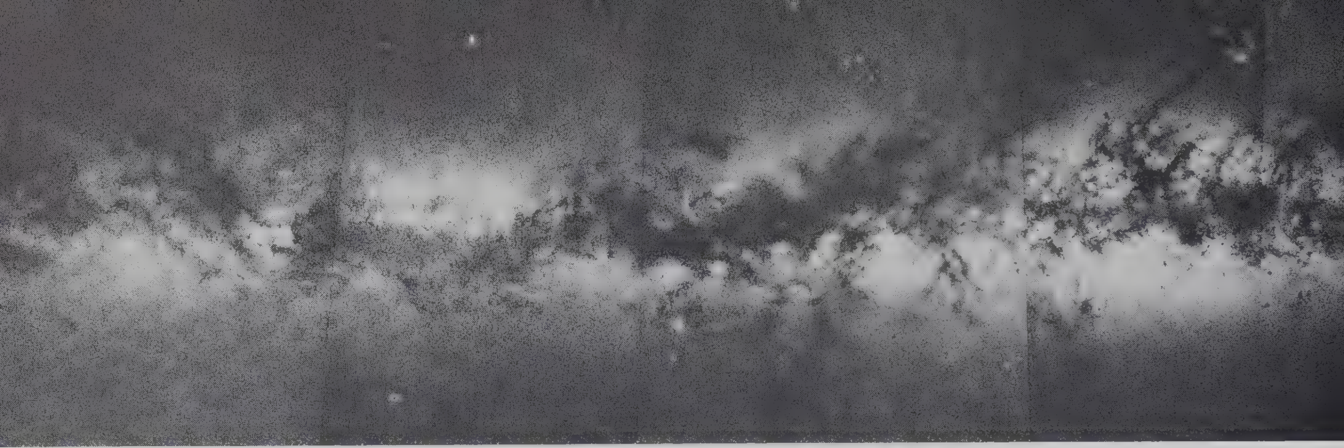


Figure 20.2 This picture, made by putting several photographs together, shows the Milky Way from Cassiopeia to Sagittarius.

too far from us to be seen with an unaided eye. It's like watching a distant city at night. You may not see the individual street lamps or neon signs, yet the city and the sky around it glow with faint radiance. So does the Milky Way, illuminated by its huge number of stars (Figure 20.2).

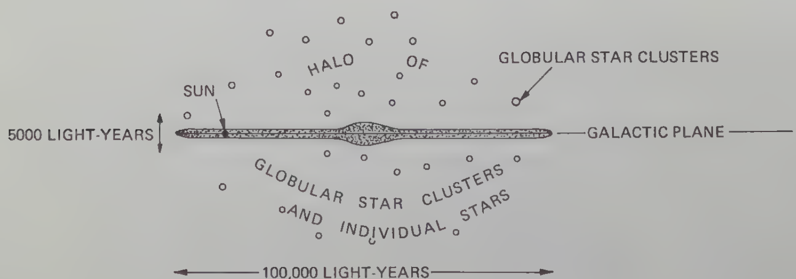
But stars surround Earth in all directions, don't they? Why then isn't the entire sky as bright as the Milky Way? What makes just a narrow luminous band arch through the constellations?

Today we know that our home galaxy, or the Milky Way system, is a disklike "island" in space made up of stars, gas, and cosmic dust. Its shape resembles that of a fried egg with a slight bulge at the center (Figure 20.3). Imagine yourself watching the sky from the inside of such a system. Would stars appear to be evenly distributed in all directions, and would the sky look uniformly bright? Perhaps more stars could be (1) seen along the galactic plane—toward the rim of the big disk? Can you now explain why the Milky Way glows with a faint light? (2)

(1) No, there would be areas of greater or lesser concentrations of stars.

(2) Obviously many stars in the rim of this disk are far too distant to be resolved individually.

Figure 20.3 A cross section of our Milky Way system would look something like this diagram.



The galaxy in Figure 20.1 is similar to our own system.(3) Known as M 33, it is two-fifths as big in diameter as the Milky Way system; it looks like a reduced model of our star island. A great concentration of stars is clearly visible at its central part. Long spiral "arms" emerging from and then coiling around the center are typical of all spiral galaxies. Figure 20.4 shows an edge-on view of the spiral galaxy NGC 4565.(4) Notice the dark belt running along its galactic plane. Any idea of what it might be? (5)

Almost 100,000 light-years in diameter, our galaxy is(6) one of the larger star islands known. Its central part, located in the direction of Sagittarius, is hidden by such thick gas and dust clouds that it has never been observed directly. But infrared astronomy—a rapidly developing branch of space exploration—has been able to detect the invisible heat rays coming from the center. The heat rays tell us that the central

(3) M33 is the 33rd object in the Messier catalog. Compiled two centuries ago, this catalog lists deep-sky objects such as clusters, nebulas, and galaxies.

(4) NGC refers to the New General Catalog compiled about a century ago.

(5) Dust and gas.

(6) A flashlight beam bright enough to shine across the Milky Way system would take more than 100,000 years to make the journey.

Figure 20.4 The spiral galaxy NGC 4565 is seen edge-on. The Milky Way system would look similar to this if seen edge-on.

region of the galaxy is a flattened group of stars about 5000 light-years across. Away from the nucleus extends a huge thin disk that contains the spiral arms with their many stars and nebulas and much interstellar matter. And all this is surrounded by a magnificent ball-shaped halo of globular star clusters and individual stars. (1)

Where is the Sun's place in this vast community of 100 billion stars? Far from enjoying the luminous central region of the Milky Way system, the Sun occupies an insignificant position in one of the spiral arms, about 30,000 light-years from the galactic center. It is from here that we are watching (2) the never-ending cosmic show.

Riding the cosmic merry-go-round. Has it ever occurred to you that you are riding a huge merry-go-round for which you have to pay no admission charge? The merry-go-round is the Milky Way system, our galaxy. Like a gigantic wheel, it turns majestically on its axis—day and night, century after century. More than 100 million years ago, when dinosaurs roamed over our planet and large parts of North America were covered by seas, the solar system was on the opposite side of the "wheel." And we'll be there again in another hundred million years from now. Just be patient and wait!

How do we know that the galaxy rotates? Imagine yourself riding a merry-go-round. As the big wheel turns, it brings you closer to some stationary objects, such as the flagpole in Figure 20.5, and carries you away from other objects, such as the tent. A similar effect can be observed in space. Spectra of two nearby galaxies—the Andromeda Spiral and the Large Magellanic Cloud—reveal that we are approaching Andromeda and moving away from the Cloud. The situation is similar (3) to the merry-go-round example, only in this case it is our own galaxy that spins on its axis.

Of course Andromeda Spiral and the Large Magellanic Cloud are not stationary objects in space. They, too, move. After corrections for their motion are taken into account, the Sun's speed through space turns out to be 270 kilometers per *second!* But even at this high a speed, the Sun needs more (4) than 200 million years to travel once around the galactic center. Since its birth 5 billion years ago, the Sun has made 23 turns by now, and we have a ticket for 23 more trips before (5) the Sun turns into a red giant and roasts all life from the surface of Earth.

(1) The distances to the star clusters were measured by means of RR Lyrae variables found in the clusters. Refer to Chapter 19 for RR Lyrae variables.

(2) Discuss how we might determine the Sun's position in the Milky Way system. Center the discussion around things like the Milky Way and the positions of the globular clusters as well as their distance from Earth.

(3) You might point out, however, that when two objects change their positions in space relative to one another, we can't tell that one is moving without another reference point.

(4) The rotation period for the Milky Way thus is about 200,000,000 years.

(5) If you had some kind of super vision and you were at this instant 5 billion light-years away, perhaps you could see the birth of the sun and the start of its first trip around the galaxy.

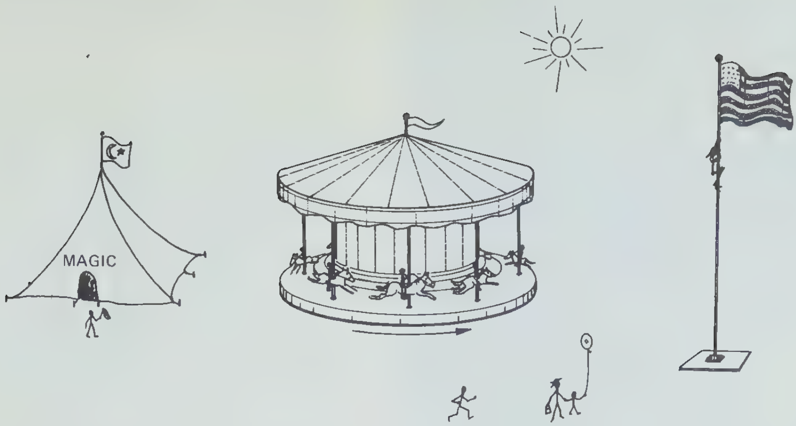


Figure 20.5 As the merry-go-round rotates, the rider is carried toward the flagpole and away from the tent.

The Sun is not alone in revolving around the galactic center. Its 100 billion sister stars do likewise. But they do not march with the same speed. Stars that are closer to the galactic center overtake and pass the Sun, while those farther away from the center fall behind the Sun. What conclusion can you make about the revolution of stars? Do they circle the galactic center in equal periods? Or does the period depend on the star's distance from the center? If so, in what way? Where else did we encounter a similar property? (6)

(6) (6) Discussing the periods of revolution of the planets and Kepler's third law.

(7) (7) **ANSWERS** / Check Your Facts

1. That of a fried egg.
2. 100,000 light-years.
3. 30,000 light-years from the center.
4. 200 million years.

CHECK YOUR FACTS

1. What is the shape of the Milky Way system?
2. What is the diameter of our galaxy?
3. Where is the Sun located in our galaxy?
4. How long does it take the Sun to travel once around the galactic center?

OTHER STAR ISLANDS

For centuries, stargazers had observed with unaided eyes faint patches in the sky. Because of their fuzzy appearance, the patches were called nebulas. ("Nebula" is Latin for "cloud.") When telescopes were introduced, Galileo, Herschel, and others discovered many more similar objects. Some of them did turn out to be huge clouds of gas and dust and others were found to be distant clusters of stars. But then there were "nebulas" that did not display the characteristics of gases or star

Figure 20.6 The beautiful Andromeda Nebula appears as a fuzzy spot to the naked eye.

clusters. The two Magellanic Clouds in the southern hemisphere and the Andromeda Nebula (Figure 20.6) were typical representatives of this group. Readily visible to the naked eye, they had been noticed already by the Arabs of the 11th century.

What is the nature of these objects? Do they belong to our own galaxy, or are they distant star islands outside the Milky Way system? For a long time, astronomers could not agree on the answer.

The solution came in 1924. In that year the American astronomer Edwin Hubble examined photographs of Andromeda Nebula and noticed that it contained a number of cepheids. But cepheids, you recall, are pulsating stars whose period enables astronomers to figure out their distances. His preliminary estimate indicated that the cepheids—and therefore the Nebula itself—were 900,000 light-years from Earth. Today we know that the distance is much greater—2.2 million light-years at least. But the distance of even 900,000 light-years placed the Nebula far outside the Milky Way system. The innocent-looking little patch in the sky had turned out to be a distant star island! Our galaxy thus was not the only star system in space. Nor was it the largest one. Having a diam-

eter of 120,000 light-years, Andromeda Spiral (as the "Nebula" was now called) is bigger than the Milky Way system both in size and in the number of stars. (1)

(1) It is also known as the Andromeda Galaxy and is an external galaxy barely visible to the naked eye on a very clear night away from city lights.

Hubble's discovery encouraged a search for other galaxies. Their number grew by leaps and bounds. In the 1930s, the number was believed to be around 30 million. By 1950 it had increased to 200 million. Today it is over a billion. Why do you think the estimated number of galaxies increases at such a rapid rate? (2)

(2) The use of more powerful telescopes and more sensitive photo plates.

Types of galaxies. Despite their great number, galaxies can be divided into three basic types—**spiral galaxies**, **elliptical galaxies**, and **irregular galaxies**.

About a half of all the brighter galaxies in our part of space are **normal spiral galaxies** like the Milky Way system and Andromeda Spiral. The beautiful object NGC 1300 seen in Figure 20.7 is a typical example of **barred spiral galaxies**. Their arms develop from the ends of a "bar" that passes through the bright center.

The two companion galaxies of Andromeda Spiral are elliptical galaxies. Do they display spiral structures? Have (3) they arms? Are they uniformly bright and equally flattened? (4)

(3) They have neither spiral structures nor arms.

(4) They appear uniformly bright, but not equally flattened.

About 3 percent of the brighter galaxies are irregular. Chaotically arranged communities of stars, they display no orderly structure or shapes. The two Magellanic Clouds—our nearest star islands—are among them. Together with Andromeda Spiral and M 33, they are the only objects outside the Milky Way system that can be seen with unaided eyes. Unfortunately, the Clouds are so far south that they can never be seen from the United States and Canada. But both are among

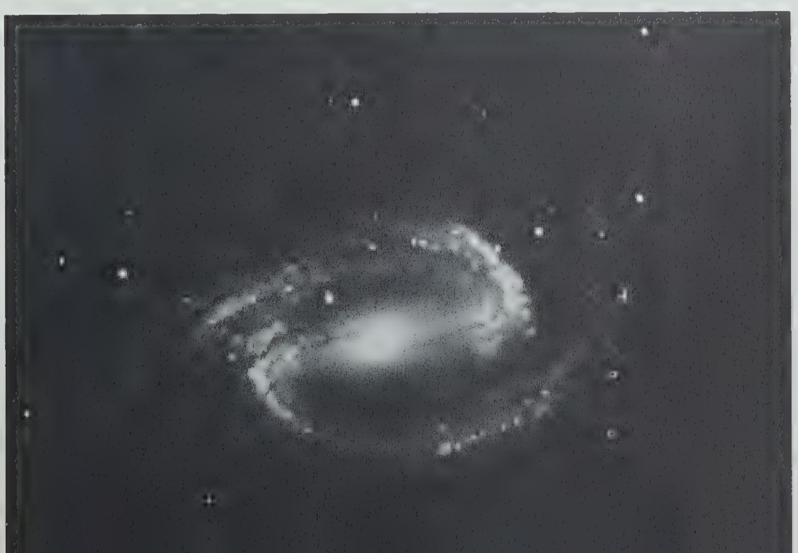


Figure 20.7 The barred spiral galaxy NGC 1300.

the best known naked-eye celestial bodies in the skies of Australia and other countries of the southern hemisphere. (1)

(1) If the charts are available, have your students find the locations of some of these galaxies on star charts and associate them with the constellations to which they belong.

CHECK YOUR FACTS (2)

(2) **ANSWERS** / Check Your Facts

1. Nebulas. [The older, Latin, plural spelling is nebulae.]
2. He showed that the Cepheids located in the Andromeda Nebula were at distances far outside our galaxy.
3. Spiral, elliptical, and irregular.

1. What did early astronomers call the faint, fuzzy patches in the sky?

2. How did Edwin Hubble demonstrate that Andromeda "Nebula" was a galaxy?

3. What are the three basic types of galaxies?

GALAXIES ARE SOCIABLE

Like stars, most galaxies prefer to spend their lives in togetherness. The two Magellanic Clouds, for instance, are a pair of closely related galaxies that accompany the much larger Milky Way system. At least a half, and possibly as much as three fourths, of all galaxies are members of double, triple, or multiple systems. Once in a while, so many galaxies are crowded together that astronomers call them **clusters of galaxies**. Some clusters contain thousands of star islands.

The Local Group. Are the two Magellanic Clouds the only star islands sharing their lives with our galaxy? To answer the question, let us do some detective work. (3)

(3) Clusters of galaxies and local groups have representatives of nearly all galactic forms.

activity 20.1 *Do nearby galaxies form a cluster?*

Examine carefully Figure 20.8. Are galaxies distributed evenly throughout the diagram, or do they display a crowding tendency around some points? Name the central galaxies of clusterings.

How many galaxies are there within a radius of 1 million light-years from us? What are the names of the two closest galaxies?

How many galaxies surround Andromeda Spiral?

Do you notice any star islands outside the Milky Way system and Andromeda Spiral families of galaxies? Name them.

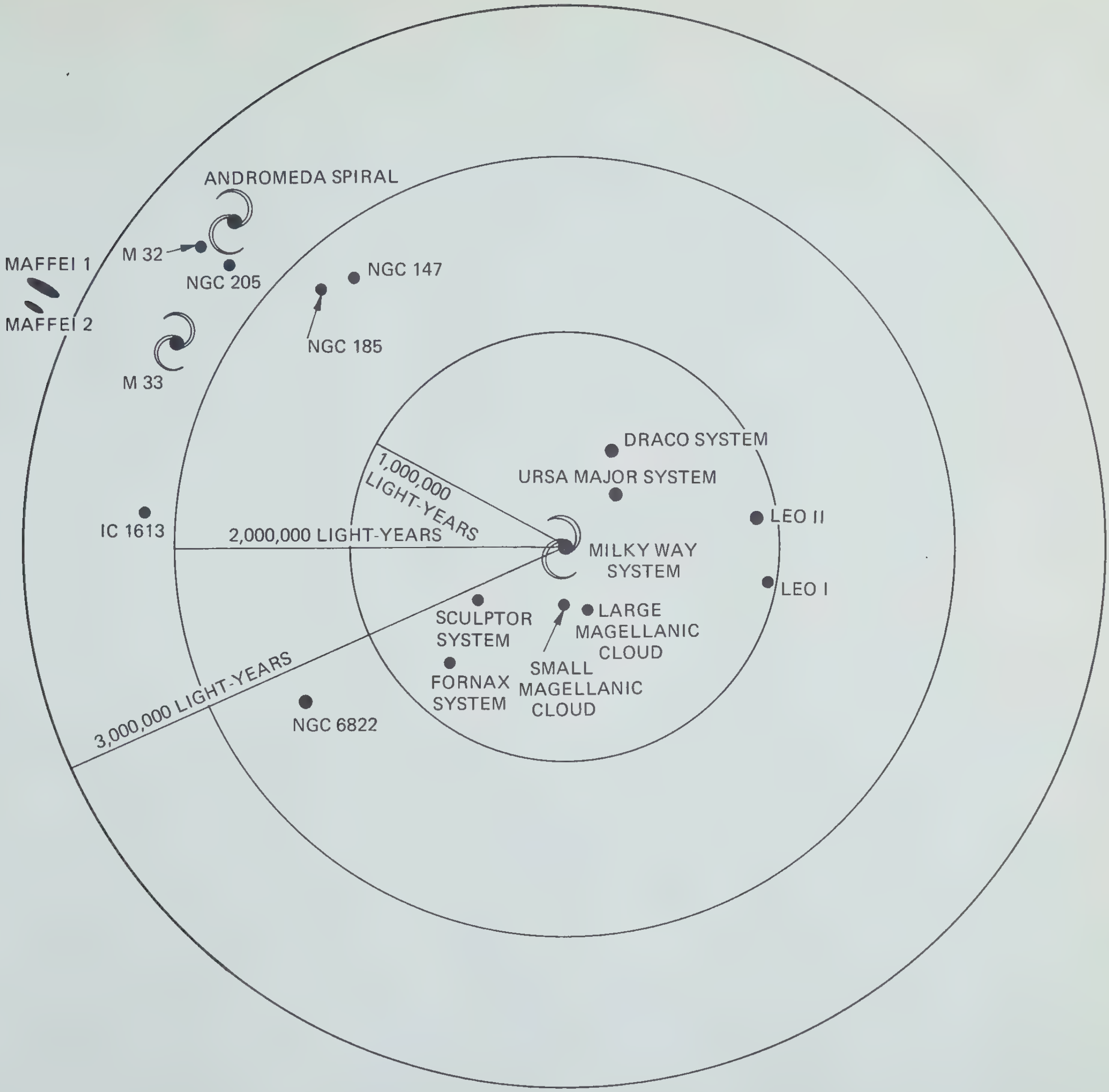


Figure 20.8 The nearby galaxies are plotted according to their distance from the Milky Way system. These galaxies together make up the Local Group.

The galaxies in Figure 20.8 make up a cluster of galaxies known as the **Local Group**. Three million light-years in length and $2\frac{1}{2}$ million light-years in width, it occupies a football-shaped part of space. Nineteen galaxies of the Local Group are presently recognized, but at least 6 more galaxies are being considered for the admission to the list.

(4) "The Starry Universe," a Life filmstrip, has some excellent illustrations of (4) members of our local group.

Rich clusters and superclusters of galaxies. De- (1) spite its membership of 19 galaxies, the Local Group is just a small cluster of galaxies. Astronomers are aware of clusters containing hundreds, even thousands of star islands. Some years ago a catalog of "rich" clusters—clusters having at least 50 galaxies each—was compiled. Can you imagine how many clusters the catalog listed? Ten thousand! Such small families as our own Local Group were not even mentioned in it.

A rich cluster of galaxies can be found in the constellation Corona Borealis (Figure 20.9). Covering an area the size of the Moon in the sky and located 700 million light-years from us, this cluster contains 400 readily recognizable galaxies. The actual membership number may be much higher.

But even clusters of galaxies are not independent units of the universe. They themselves appear to be gathering into

(1) The *Hubble Atlas of Galaxies*, published by the Carnegie Institution of Washington, is an excellent reference to use here. It has some of the best photographs of galaxies ever published.

Figure 20.9 Many galaxies can be seen in this photograph of the central portion of the Corona Borealis cluster.

Figure 20.10 This supercluster in the constellation Hercules is made up of many smaller clusters of galaxies.

still larger building blocks known as **superclusters**. The Local Group, together with the rich Virgo cluster and several smaller clusters of galaxies, form the Local Supercluster. Far beyond its boundaries, photographs reveal many other similar superunits. The great assemblage of galaxies in Hercules (Figure 20.10) is one of them.

Superclusters of galaxies do not thin out with an increasing distance from Earth. Space 3 billion light-years away looks similar to that around us. The vastness of the universe is overwhelming—and man is so hopelessly small.

CHECK YOUR FACTS

1. Name some galaxies that are closely associated with our galaxy.

2. Is the Local Group a big cluster?

3. Do clusters form still larger units?

(1) (1) **ANSWERS** / Check Your Facts

1. The Magellanic Clouds, Sculptor, Fornax, Ursa Major, Draco, Leo I, and Leo II.
2. No.
3. Yes.

THE STRANGE QUASARS

We mentioned in Chapter 18 that celestial bodies emit energy in a wide range of wavelengths. While most of it reaches us as visible light, a good deal of it arrives in the form of invisible infrared, ultraviolet, and radio waves.

Since 1931, when radio waves from outer space were first detected, astronomers have been studying radio waves from a variety of celestial bodies, such as the Sun, Jupiter, and certain nebulas and supernovas. For a long time, however, no radio waves were detected from a "normal" star—except, of course, the Sun. The radio emission of stars was believed to be too weak to be detected by present-day astronomical equipment. No wonder, then, that astronomers were taken by surprise when, back in 1960, the first two starlike "radio stations" of the universe were discovered. By the time of writing this text, their number already exceeds two hundred. Known as quasi-stellar objects, or simply **quasars**, they opened one of the most controversial chapters in recent astronomy. Dozens of international astronomical conferences have dealt with the problem, yet the true nature of quasars still remains a mystery.

What's so unusual about quasars? If an average star such as the Sun can emit radio waves, why couldn't other stars do the same? There are several reasons why quasars appear to be strange objects. In fact, it is possible that they may not be stars at all.

First, the red shift of the spectra of quasars seems to indicate that quasars are receding from us at fantastic speeds.

The distance to quasar 3C48, for instance, increases at the rate of more than 100,000 km per second! (2)

Second, the high speeds of recession suggest that quasars must be very distant celestial bodies. Some of them appear to be dwelling far beyond the realm of the most remote galaxies known. To cast their light through such distances, quasars must radiate tens, if not hundreds of times more energy than does the entire Milky Way system with all its stars. We could, therefore, expect quasars to be mighty big celestial bodies. But they are not. In fact, some of them occupy a volume less than one-hundred-trillionth part of our own galaxy. As if this were not confusing enough, many quasars vary in both their light and radio output; 3C273 is an example.

What are the mysterious objects? Are they supergigantic stars, collapsing galaxies, or parts of star islands ejected from their home galaxies? And how sure can we be that the high red shifts are caused by the recession rather than by some other phenomenon, such as an extremely high gravitational force of the quasars themselves? If so, aren't quasars members of our own Milky Way system? (3)

These are but some of the thoughts that have crossed the minds of astronomers since the first two quasars were discovered. Which, if any, of them is correct, no one knows. The right answers seem to have escaped astronomers—for the time being, at least. (4)

CHECK YOUR FACTS

1. What are some astronomical bodies from which radio waves have been detected?

2. What are some unusual properties of quasars?

THE EXPANDING UNIVERSE

Do you know of a single celestial body that stays motionless in space? Think of what would happen to the Moon if it suddenly stopped revolving, or to planets if they decided to take it easy and slow down in their orbits, or to the Milky Way system if it ceased turning. (5)

Astronomers realized long ago that galaxies, too, must be moving, or else the universe would fall together. But all the efforts to observe their motions across the line of sight

(2) The astronomer Hubble said that an object increases its velocity by 30 km/sec for every million light-years of distance. Therefore, this object could be a long way off!

(3) We simply don't know the answers to all these questions.

(4) **ANSWERS** / Check Your Facts

1. The Sun, Jupiter, and quasars.
2. Extremely high speed of recession, extremely great distances from us, extremely high energy production accompanied by small size.

(5) None.

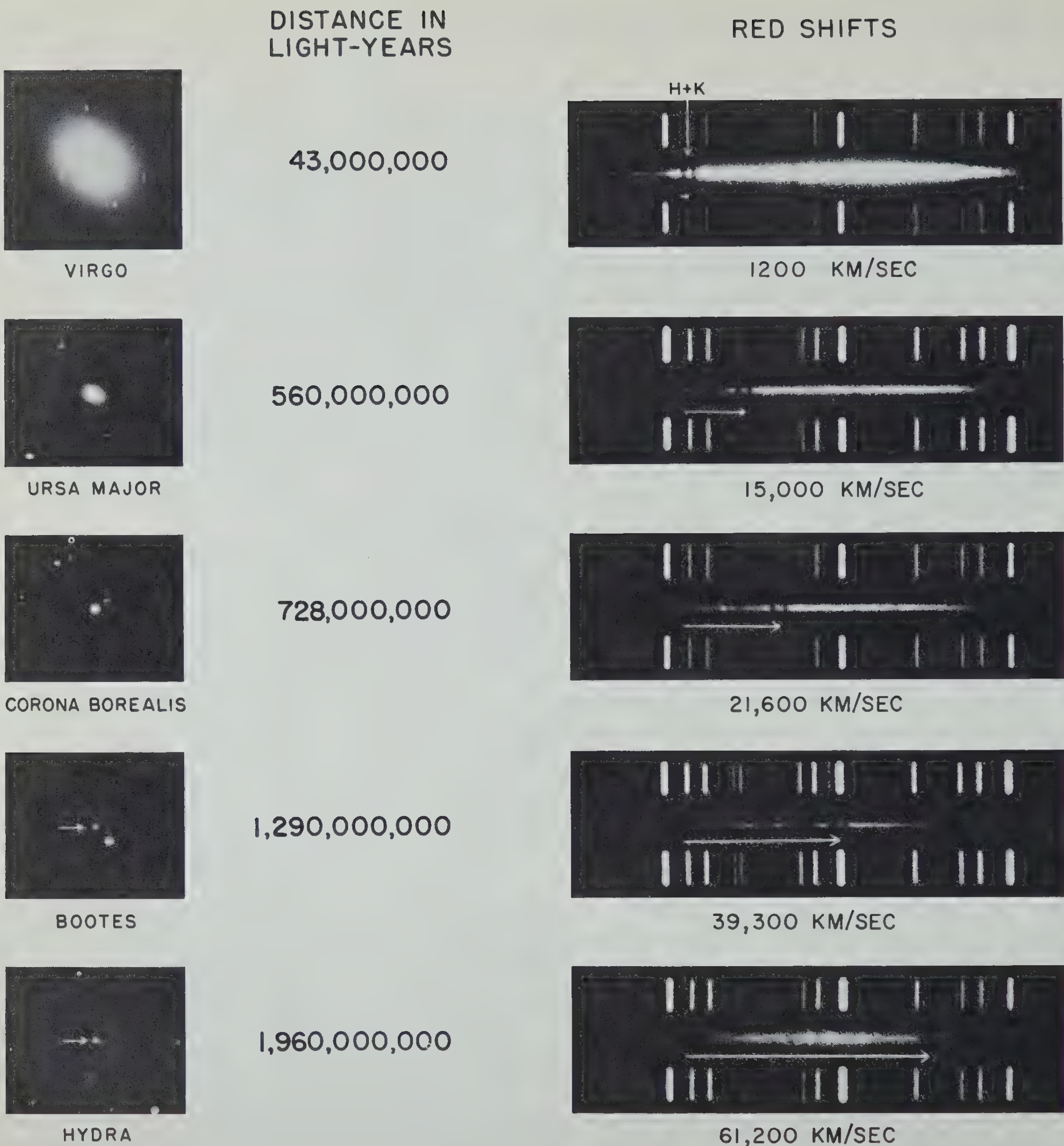


Figure 20.11 Five galaxies are shown at left and their spectra are shown at right.

have failed. Even your lifetime and mine would not be long enough to notice any changes in their positions. Can you guess why not? (1)

The story is different when it comes to motions along the line of sight. As in the case of stars, such motion can be measured by means of the Doppler shift in the spectra of galaxies.

(1) The galaxies are too far away. The displacement of a few light-years would be unnoticed at a distance of millions of light years.

Examine the spectra of galaxies in Figure 20.11, for instance. There is not much to see in them except for two dark lines. Yet these lines tell us an interesting story. Labeled as the H and K lines, they are absorption lines produced by calcium in the galaxies.

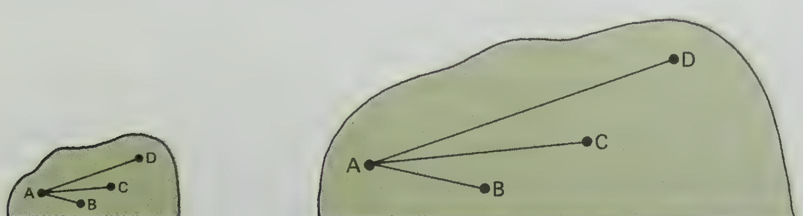
On the left in Figure 20.12 are photographs of galaxies located at increasingly greater distances—from 43 million light-years for a galaxy in the constellation Virgo (top photograph) to 1.96 billion light-years for a galaxy in the constellation Hydra (bottom photo). The spectrum of each galaxy is shown to its right. The horizontal arrow in each spectrum indicates how much the H and K lines are red-shifted; from the amount of the red shift, the speed of recession of that galaxy can be determined. These speeds are given under the spectra.

A look at Figure 20.12 immediately brings out a very simple and very startling relationship between a galaxy's distance and its speed of recession. The farther away the galaxy, the faster it recedes from us! This relationship led astronomers to one of the most important findings of 20th-century astronomy: The universe is expanding.

activity 20.2 *The expanding raisin-cake universe*

Why do the more distant galaxies move away faster? To understand this, let's consider the behavior of raisins in an expanding raisin cake. Suppose that the raisin cake in Figure 20.12 expands from the size at left to the size at right in an hour. As it expands, the raisins A, B, C, and D recede from one another. What can you say about the *speeds* with which the raisins recede from one another—from A, for instance?

Figure 20.12 Galaxies in an expanding universe can be compared to raisins in an expanding raisin cake.



To answer this question, complete the following table and examine the results in the two last columns.

Raisins	**Original distance from A**	**Distance from A an hour later**	**Speed of recession from A**
B	**1 unit**	**3 units**	**2 units per hour**
C	**2 units**	**? units**	**? units per hour**
D	**3 units**	**? units**	**? units per hour**

Do all the raisins recede from A at the same speed? Or do they behave like galaxies in the universe: The greater the distance, the faster they recede? Do you see now why the more distant galaxies move away from us faster in an expanding universe?

Continuous creation, or a big bang? What makes the universe expand? Astronomers wish they knew. (1) Around the middle of this century, some astronomers suggested that the universe is still in creation. New matter, they said, is always being created. The process of creation goes on throughout the universe and it will never end. But as the newly emerging atoms exert a push upon their older neighbors, the universe expands, much as a balloon expands when more and more air is forced into it. It is for this reason, argue the proponents of the Continuous-Creation theory, that the older galaxies recede from us, while new star islands evolve from the recently born matter. Except for minor local variations, the overall picture of the universe remains unchanged throughout eternity, no matter where it is watched from. This is why the Continuous-Creation theory is sometimes called the Steady-State theory.

(1) Unknown. The answer is hidden in the origin of the universe.

How much matter do you think should be created to bring about the observed expansion? An atom per cubic centimeter daily? Perhaps a million atoms? Nothing of that order. The birth, on the average, of one single hydrogen atom in a cubic kilometer of space in four centuries would do the trick!

The Continuous-Creation theory has a weak point; it violates one of the basic principles of physics, namely that matter cannot be created from nothing. Yet it has appealed to many astronomers. The latest observations, however, appear to discredit the theory. Among them are signs indicating that the expansion of the universe is slowing down. If this is indeed the case, then it contradicts the basic assumption of the theory that the universe remains unchanged forever. (2)

(2) After supporting the steady-state theory for many years, the English astronomer Fred Hoyle, one of its original proponents, admitted that he might have been mistaken.

According to another theory, the universe might have developed from a gigantic explosion that occurred some 10 billion years ago. This is known as the Big Bang theory. Before the big bang (the explosion), the entire matter of the universe had contracted into a single body, perhaps as small as the size of the solar system. If you suspect that the density and the temperature of such a ball must have been fantastically high, you are right. At the time of the explosion, each cubic centimeter of the compressed stuff forming the ball contained 80 million tons of mass, and its temperature was several billion degrees!

When the great explosion took place, the ball burst into pieces like a gigantic Fourth of July firework. The glowing gases dispersed into space at enormous speeds. It is from this material that stars and galaxies evolved and that Earth with its streams, orchards, busy cities, and everything else came into existence. You may find it hard to imagine that your own lively and delicate body is made up of particles that once resided in the sweltering and immensely compressed interior of the original ball.

Contrary to the Continuous-Creation theory, which predicts a never-ending universe, the Big Bang theory draws a gloomy picture. As galaxies continue receding from one another, their light will grow fainter and space will become emptier. With no way of replenishing the used up hydrogen supply, stars will inevitably approach the ends of their lives. Dimming like theatre lights before a show, they will eventually leave the universe dark and lifeless.

But the Big Bang theory is by no means the final word in predicting the future of the universe. If the expansion is really slowing down, as some astronomers believe it is, what would you expect to happen eventually? Will the universe continue growing infinitely big, or is the expansion bound to stop some day? And what will happen then? Only one outcome seems possible—the collapse of the universe due to its own gravitational force. At first hardly noticeable, the rate of shrinking will increase gradually. Eventually the collapsing universe will become so crowded that galaxies will ram into each other, stars will explode in blinding collisions, planetary systems will evaporate, and the universe itself will once again turn into a superhot and enormously dense ball.

Will this mark the end? Nobody knows. Our present universe, of course, will have ceased to exist. But it is tempting to assume that another Big Bang might bring another uni-

verse into being. If so, the cosmic show will probably repeat itself. Galaxies and stars will emerge, and life will ultimately evolve on some cosmic cinders. Stargazers of those far-away tomorrows will watch the receding galaxies and ask the same questions we are asking today: What is the universe like? Is it finite or infinite? Does it pulsate or just expand? Where did all this come from and what is its destiny?

(1) **(1)** The pulsating universe is sometimes called the oscillating universe.

These are difficult questions to answer. Our knowledge about the birth and death of the universe is badly restricted. The brilliance of the creation had faded away long before Earth appeared on the scene, and the future of the universe is still a mystery. Confined to spend his little life between the two great unknowns—the beginning and the end—man traces eagerly the outlines of the universe wondering about his own place and mission in it.

(2) **(2)** This would be a good point at which to show the film "The Universe," produced by the National Film Board of Canada. This film is 12 years old, but still worth showing.

CHECK YOUR FACTS

1. How do we measure a galaxy's speed of motion along the line of sight?

2. What is the relationship between a galaxy's distance and its speed of recession?

3. What are some differences between the Continuous-Creation theory and the Big Bang theory?

(3) **(3) ANSWERS** / Check Your Facts

1. By the amount of its red shift.
2. There is a direct relationship; the greater the speed of recession, the greater the distance.
3. See pages 422-424.

APPLYING WHAT YOU HAVE LEARNED

1. Are there any objects outside the Milky Way system visible to the naked eye? Can they be seen from the United States?

2. What makes us conclude that the Milky Way system does not have a ball-like shape?

3. How are distances to nearby galaxies measured? Do you think the same method could be applied to galaxies billions of light-years from us?

4. Quasars are among the most controversial celestial bodies discovered recently. List some of their properties.

5. Astronomers believe that the universe expands. Would this mean that Earth, buildings, coins in your pocket, and even a rock on a lake shore grow bigger?

6. Name a few kinds of celestial bodies that emit radio waves.

(4) **(4) ANSWERS** / Applying What You Have Learned

1. The Andromeda Spiral (Galaxy), the M33 spiral, and the two Magellanic Clouds. However, the Clouds are only visible from the Southern Hemisphere.
2. The concentration of stars near the galactic plane and lack of them in other directions.
3. By means of the Cepheids in them. No.
4. See pages 418-419.
5. For all practical purposes, no; theoretically, over a *long* period of time, yes. This would be an interesting topic for class discussion in a class of sufficiently high caliber.
6. Stars, some galaxies, quasars, and pulsars.

KEY WORDS

spiral galaxy (p. 413)
elliptical galaxy (p. 413)
irregular galaxy (p. 413)
normal spiral galaxy (p. 413)
barred spiral galaxy (p. 413)
cluster of galaxies (p. 414)
Local Group (p. 415)
supercluster (p. 417)
quasar (p. 418)

appendixes

appendix 1 Powers of ten

In science, it is often necessary to use very large and very small numbers. The area of Earth's surface is 361,000,000 square kilometers. A convenient shorthand for writing numbers like this one is to use powers of ten. For example,

Number	Equivalent power of 10	Number	Equivalent power of 10
$1000 =$	10^3	$0.1 = \frac{1}{10^1}$	$= 10^{-1}$
$100 =$	10^2	$0.01 = \frac{1}{10^2}$	$= 10^{-2}$
$10 =$	10^1	$0.001 = \frac{1}{10^3}$	$= 10^{-3}$
$1 =$	10^0	$0.0001 = \frac{1}{10^4}$	$= 10^{-4}$

The number 361,000,000 is the same as 3.61 times 100,000,000. Since this is 3.61 times $10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10$ or 3.61 multiplied by 10 eight times, we write it as 3.61×10^8.

exponent

$$\text{coefficient} \longrightarrow 3.61 \times 10^8$$

base

The *exponent* tells how many times to multiply by 10, which is called the *base*. To convert a number from the usual long form to the standard form, move the decimal point to the left until you have a number between one and ten. The number of places that you moved the decimal point is the exponent, or power of ten. The coefficient is the number between one and ten used with the power of ten. In the example, the decimal point was moved eight places to the left, so the exponent is 8. The base is 10 since we are using the decimal number system. The coefficient is 3.61.

If the original long number is less than one, it can be expressed as a number between one and ten *divided* by ten to some power.

$$0.008 = 8 \times \frac{1}{1000} = 8 \times \frac{1}{10^3} = 8 \times 10^{-3}$$

That is, if you have to move the decimal point to the *right* to get a number between 1 and 10, the exponent has a negative sign.

appendix 2 Some prefixes used in naming metric units

Prefix	Meaning	Example
giga	10^9	one gigameter = 10^9 meters
mega	10^6	one megameter = 10^6 meters
kilo	10^3	one kilometer = 10^3 meters
centi	10^{-2}	one centimeter = 10^{-2} meters $= \frac{1}{100}$ meter
milli	10^{-3}	one millimeter = 10^{-3} meter $= \frac{1}{1000}$ meter
micro	10^{-6}	one micrometer = 10^{-6} meter = one micron (μ)
nano	10^{-9}	one nanometer = 10^{-9} meter

appendix 3 Conversion between metric and British units*

*Metric units of measurement (such as the meter and the gram) are used in most scientific work throughout the world. British units (such as the foot and the pound) are used in the United States in engineering, in some scientific work, and in commerce. Britain, where British units originated, has switched to metric units. Canada and most other countries presently using British units plan to switch to metric units in the future. Values given in the tables below are, in most cases, approximate. The table for mass needs an explanation. The *mass* of a body is a quantity that does not change no matter where the body is located in the universe. The *weight* of a body is the force of gravitational attraction between that body and some other body. Your weight, for example, is the force of attraction between you and Earth. The force of attraction between you and Earth (assuming you are on Earth's surface) is about six times stronger than the force of attraction between you and the Moon (assuming you are on the Moon's surface). Thus, your weight on Earth is about six times your weight on the Moon. Your mass, however, remains the same. The gram (as well as related units such as the kilogram and milligram) is a metric unit of *mass*, and the pound is a British unit of *weight*. For the sake of convenience, they are often treated as the same kind of unit, even though they really are not. For example, the mass table below indicates one kilogram as being equal to 2.2 pounds. Actually, the weight of a one-kilogram mass on Earth is 9.8 newtons. (The newton is the unit of force or weight in the metric system.) Thus, it would be more correct to say that 9.8 newtons = 2.2 pounds, rather than that 1 kilogram = 2.2 pounds.

Metric to British		British to metric	
Length			
one centimeter (cm)	= 0.394 inch	one inch	= 2.54 cm
one meter (m)	= 39.4 inches	one foot	= 0.305 m
one kilometer (km)	= 0.621 mile	one mile	= 1.61 km
Area			
one sq. centimeter (cm^2)	= 0.155 sq. inches	one sq. inch	= 6.45 cm^2
one sq. meter (m^2)	= 10.8 sq. feet	one sq. foot	= 0.093 m^2
one sq. kilometer (km^2)	= 0.386 sq. mile	one sq. mile	= 2.59 km^2
Volume			
one milliliter (ml), also called one cubic centimeter (cc)	= 0.034 liquid ounces	one liquid ounce	= 29.6 ml
one liter (1)	= 1.06 liquid quart	one liquid quart	= 0.946 l
Mass			
one gram (g)	= 0.035 ounce	one ounce	= 28.3 g
one kilogram (kg)	= 2.2 pounds	one pound	= 0.454 kg
one metric ton	= 1.1 short tons	one short ton	= 0.907 metric ton

appendix 4 Celsius and Fahrenheit scales

The Celsius temperature scale, also called the centigrade scale, is used in most scientific work. In this scale, there are 100 degrees between the freezing point of water (0°C) and the boiling point of water (100°C). In the Fahrenheit scale (used for commerce in the United States but being dropped by most other English-speaking countries), the freezing point of water is −32°F and the boiling point of water is 212°F. To change a Celsius value to its equivalent in Fahrenheit, use the formula $F = \frac{9}{5}\ C + 32$. To change from Fahrenheit to Celsius, use the formula $C = \frac{5}{9}\ (F–32)$.

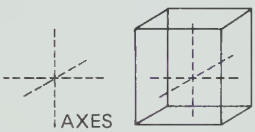
appendix 5 Crystal systems

Hundreds of different crystal forms are found in nature, but all of them can be classified into six large groups called crystal systems. The different systems are determined by the relationships of imaginary axes that connect opposite corners or opposite faces and that intersect at a point.

All minerals are crystalline—that is, each mineral has a definite internal arrangement of the ions. However, good crystals require space in which to grow: therefore crystals that have well-developed forms and are large enough to see without a magnifying glass are rare.

<table>
<tr><th>Crystal systems</th><th>Sample minerals</th></tr>
<tr><td>

Cubic (Isometric)
(3 axes of equal length, intersecting at right angles)



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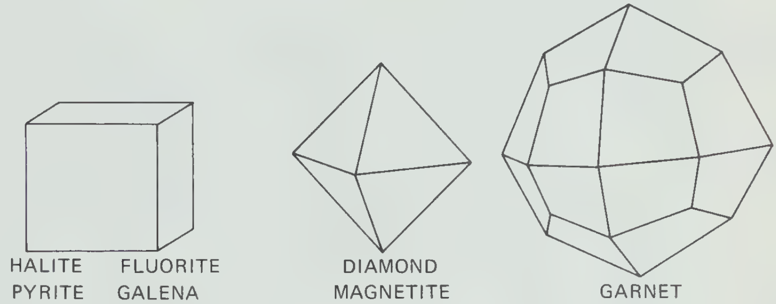

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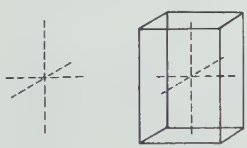
Tetragonal
(3 axes, 2 of equal length and horizontal, and a vertical axis that is longer or shorter than the horizontals)



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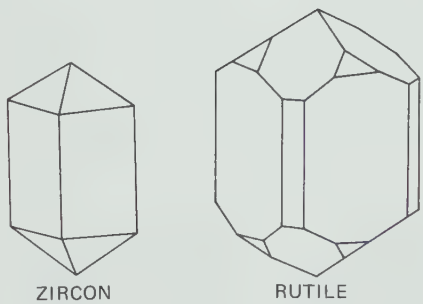

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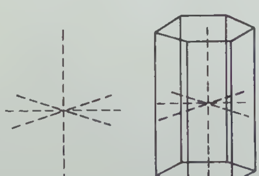
<tr><td>

Hexagonal
(4 axes, 3 of equal length and horizontal and intersecting at angles of 60°, and a vertical axis that is longer or shorter than the horizontal axes)



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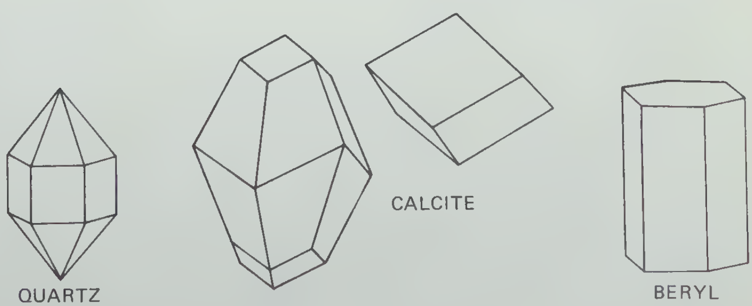

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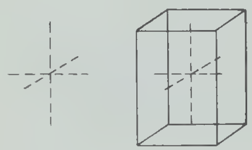
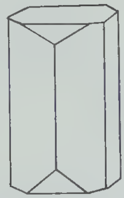
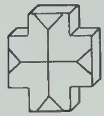
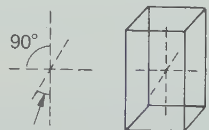
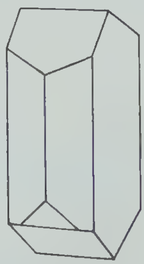
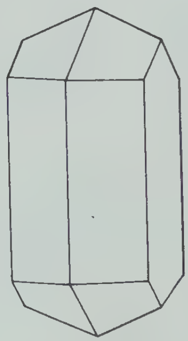
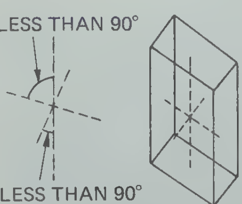
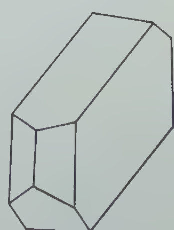
</table>

Crystal systems	Sample minerals
Orthorhombic (3 axes of different lengths and intersecting at right angles) 	 STAUROLITE  STAUROLITE (TWIN)  BARITE
Monoclinic (3 axes of different lengths, 2 intersecting at an oblique angle and the third perpendicular to them)  LESS THAN 90°	 ORTHOCLASE   GYPSUM
Triclinic (3 axes of different lengths and intersecting at different angles) LESS THAN 90°  LESS THAN 90°	 PLAGIOCLASE

appendix 6 Mineral identification

Chemical analysis and X-ray study are used in sophisticated mineral studies, but most of the common minerals can be identified by their easily observable physical properties. The most important properties are described below:

Color. Color is the most obvious physical property of a mineral. For a few minerals, it is a good aid in identification. (For example, sulfur is yellow, galena is steely gray, and olivine is green.) However, the color of most minerals is variable, because small amounts of impurities can change the color.

Streak. The "streak" of a mineral is the color of its powder. Rather than grind up some mineral each time, a quicker way to observe the streak is to scratch the mineral on an unglazed porcelain plate. The color of the powder is commonly different from the color of the mineral specimen. Streak is a good identifier for a few minerals, such as limonite (yellow to yellow-brown) and hematite (red to red-brown).

Crystal form. A few minerals, such as calcite, quartz, garnet, fluorite, pyrite, and galena, are commonly found as well-formed crystals. The crystal form (see Appendix 5) is then of value in their identification. However, well-formed crystals of most minerals large enough to see are not common.

Cleavage. The tendency of a mineral to break or "cleave" along parallel sets of flat, shiny surfaces called cleavage planes is an aid in identifying many minerals. Cleavage results from planes of weakness, due to weaker bonds, in the crystal structure. A mineral with cleavage breaks more readily along those planes than across those planes. Mica has one cleavage, orthoclase and plagioclase have two cleavages at right angles, amphibole has two cleavages at angles of about 60° and 120°, halite has three cleavages at right angles, and calcite has three cleavages not at right angles. Some minerals, such as quartz and olivine, have no cleavages.

Hardness. Hardness is an easily measured property. The table below is the Mohs hardness scale. Any mineral on the scale will scratch one with a lower number. (When a mineral is scratched, ions are separating from the crystal structure. If the bond holding the ions is weak, the mineral is soft. If they are strong, the mineral is hard.) Of course we rarely have this set of minerals in the field, so the relative hardness of some common "tools" is also given.

Hardest	10	Diamond	
	9	Corundum	
	8	Topaz	
	7	Quartz	
	6	Orthoclase	
		$5\frac{1}{2}$ Glass	
	5	Apatite	5 Nail or knife
	4	Fluorite	
	3	Calcite	3 Copper penny
		$2\frac{1}{2}$ Fingernail	
	2	Gypsum	
Softest	1	Talc	

Luster. Luster is the appearance of a mineral in reflected light. "Metallic" and "nonmetallic" are the two types of luster. For example, pyrite is metallic. Quartz is nonmetallic, and its luster can further be described as "glassy." Clay is "dull." Common words are used to define the luster of a mineral—call it as you see it.

Specific gravity. In Activity 4.7 you determined the specific gravity of minerals by comparing their weights to the weight of an equal volume of water. The simplest way to determine this property, when great accuracy is not required, is to compare the weight or "heft" of samples of similar size. For example, a piece of galena is "heavy," whereas a piece of quartz the same size is "light."

Other physical properties. Calcite "fizzes" or reacts with acid, magnetite is attracted to a magnet, halite tastes salty, and clay has an "earthy" odor. Some other properties are not included in this appendix because they are of use in the identification of only a few minerals.

The following three mineral identification charts contain the common minerals, plus some others. Using them is simply a process of elimination. Note that Chart I includes minerals with metallic luster, Chart II includes dark-colored minerals with nonmetallic luster, and Chart III includes light-colored minerals with nonmetallic luster. Note that hardness and cleavage are determined next. Then the listed properties are used to make the final identification.

Mineral identification charts

I. Metallic luster

Steel gray; shiny; marks paper and smudges fingers; hardness (H) = 1-2	**Graphite** C
Shiny gray; very heavy; perfect cubic cleavage; lead-gray streak; H = $2\frac{1}{2}$	**Galena** PbS
Soft yellow color; becomes paler with increase in percentage of silver; very heavy; H = $2\frac{1}{2}$-3	**Gold** Au
Coppery-red on fresh surfaces; often greenish on old surfaces; heavy; H = $3\frac{1}{2}$	**Native copper** Cu
Deep brassy yellow; greenish-black streak; brittle; no cleavage; H = 4	**Chalcopyrite** $CuFeS_2$
Black; metallic to sub-metallic luster; magnetic; black streak; H = 6	**Magnetite** Fe_30_4
Steel-gray to black; reddish to reddish-brown streak; H = 5-$6\frac{1}{2}$	**Hematite** Fe_20_3
Pale brassy yellow; cubic crystals; greenish-black streak; H = 6-$6\frac{1}{2}$	**Pyrite** FeS_2

II. Nonmetallic luster (dark-colored)		
Scratch glass	Cleavage	Dark green or black; 2 directions of cleavage nearly at 90°; H = 5-6 **Pyroxene** Ca, Fe, Mg, Al, Si, O
		Dark green or black; splintery; 2 directions of cleavage at 60° and 120°; H = 5-6 **Amphibole** Ca, Na, Fe, Mg, Al, Si, O
	No cleavage	Red-brown to brownish black; often dull when altered; crosses (twinned crystals) common; H = 7-7½ **Staurolite** Fe, Al, Si, O
		Wine-red; curved fracture; often 12-sided crystals; parting (not cleavage) common; H = 6½-7½ **Garnet** Ca, Mg, Fe, Mn, Al, Si, O
		Commonly black or blue, but various colors; crystals have triangular cross section; good crystals common; curved fracture; H = 7-7½ **Tourmaline** Na, Ca, Fe, Bo, Al, Si, O
		Various colors; greasy to glassy luster; transparent to translucent; curved to uneven fracture; H = 7 **Quartz** SiO_2
Do not scratch glass	Cleavage	Black to brown; 1 perfect cleavage; elastic; H = 2½-3 **Biotite** H, K, Mg, Fe, Al, Si, O
		Various shades of green; 1 cleavage; nonelastic; H = 2½-3 **Chlorite** H, Mg, Fe, Al, Si, O
		Yellow-brown to black; pale yellow streak; H = 3½-4 **Sphalerite** ZnS
		Light to dark brown; glassy luster; 3 directions of cleavage, none at right angles; H = 3½-4 **Siderite** $FeCO_3$
	No cleavage	Steel gray to reddish brown; variable luster; reddish to reddish-brown streak; H = 2-6½ (variable) **Hematite** Fe_2O_3
		Yellow-brown to dark brown; yellow to yellowish-brown streak; H = 1½-5 (variable) **Limonite** $Fe_2O_3 \cdot H_2O$

III. Nonmetallic luster (light-colored)

Scratch glass	Cleavage	Pink to white; 2 cleavages at 90°; glassy luster; H = 6	**Orthoclase** K, Al, Si, O
		White, blue, gray; 2 cleavages; striations (fine parallel line due to twinning); H = 6	**Plagioclase** Na, Ca, Al, Si, O
	No cleavage	Various colors; greasy to glassy luster; transparent to translucent; curved to uneven fracture; H = 7	**Quartz** SiO_2
		Olive green; glassy luster; transparent to translucent; curved fracture; H = 7	**Olivine** Fe, Mg, Si, O
Do not scratch glass	Cleavage	Colorless to white; cubic cleavage; salty taste; $H = 2\frac{1}{2}$	**Halite** NaCl
		Clear, white to yellow; 3 cleavages, none at right angles; fizzes in acid; H = 3	**Calcite** $CaCO_3$
		White to transparent; nonelastic; 1 cleavage; H = 2	**Gypsum** $CaSO_4 \cdot H_2O$
		White to green; soapy feel; pearly luster; H = 1	**Talc** H, Mg, Si, O
		Colorless to light gray; transparent; 1 perfect cleavage; elastic; $H = 2\text{-}2\frac{1}{2}$	**Muscovite** H, K, Al, Si, O
		White, purple or green of various shades; 4 cleavages; cubic crystals; H = 4	**Fluorite** CaF_2
		Tan to white; pearly luster; fizzes in acid if powdered; $H = 3\frac{1}{2}\text{-}4$	**Dolomite** $CaMg(CO_3)_2$
		Light to dark brown; glassy luster; 3 directions of cleavage, none at right angles; $H = 3\frac{1}{2}\text{-}4$	**Siderite** $FeCO_3$
		White, colorless, other light shades; heavy; $H = 3\text{-}3\frac{1}{2}$	**Barite** $BaSO_4$
	No cleavage	Yellow of various shades; light weight; $H = 1\frac{1}{2}\text{-}2\frac{1}{2}$	**Sulfur** S
		White, brown, gray; earthy odor when damp; slippery feel; $H = 2\text{-}2\frac{1}{2}$	**Clay** (Kaolinite) H, Al, Si, O
		Tan to buff; small round structures; H = 1-3	**Bauxite** $Al_2O_3 \cdot H_2O$

appendix 7 Rock identification

The most common rock types are briefly described here. There are many variations of each rock type, and there are many uncommon rock types, so you may not be able to identify every rock you find. All rocks are classified according to *texture* and *composition.*

Igneous rocks

Granite: Coarse grained, light colored (gray, pink, or red). You can usually identify in it clear, glassy quartz; pink or white feldspars with cleavage; and black biotite or amphibole.

Gabbro: Coarse grained, dark colored (dark gray to black). Gray plagioclase usually is the dominant mineral; pyroxene, olivine, and magnetite, dark green to black, are also found.

Rhyolite: Fine grained, light colored (light gray, pink, or red). Same minerals as in granite. Will scratch glass. May show "banding" due to flow of lava.

Basalt: Fine grained, dark colored (dark gray to black). Same minerals as in gabbro. Will scratch glass. Commonly contains rounded gas cavities (called *vesicles* when empty and *amygdules* when filled with calcite, quartz, or other minerals).

Sedimentary rocks

It is not always easy to classify a sedimentary rock as a particular type, as there are often many gradations from one sedimentary rock type to another. (For example, conglomerate sandstone is classified as a sandstone, but it has some of the characteristics of conglomerates. As another example, sandy limestone is classified as a limestone, but it has some of the characteristics of a sandstone.)

Conglomerate: Rounded pebbles (or larger particles) in a finer-grained material. Pebbles can be white "milky" quartz from quartz veins, but are usually made of other rocks.

Sandstones: Sand-sized grains, rough to the touch. Will scratch glass, as the grains are often made up of quartz and feldspars. In **quartz sandstone**, all grains are made of glassy quartz. It is white to yellow, brown, or red if iron oxides are present. **Arkose sandstone** has pink or white feldspar grains (some chalky white due to partial change to clay). It is commonly light gray, brown, or red. **Graywacke sandstone** may have grains of anything plus clay. It is commonly dark green to dark gray.

Siltstone: Silt-sized grains. Rough to the touch but not as rough as sandstone. Any color. Will scratch glass, as its minerals are commonly the same as those in sandstone.

Mudstone: Clay with silt grains. Will scratch glass with difficulty if at all. Blocky chunks. Commonly black, gray, green, or tan.

Shale: Same as mudstone, but breaks into small flat chips.

Limestone: Highly variable grain size. Fossils common. Won't scratch glass. As it's made of calcite, will fizz in dilute hydrochloric acid. Color varies from white to black due to impurities, but usually light.

Chert: Finely crystalline siliceous rock, of organic or precipitated origin. Scratches glass easily. Can be almost any color, but white, gray, black, or reds are most common. Breaks with curved (conchoidal) fracture.

Dolomite: Similar to limestone (generally formed from limestone), but buff-colored. Small irregular cavities and/or rough "pock-marked" surface common. Fossils rarer. Will fizz in acid only when scratched (the powder fizzes).

Metamorphic rocks

Any rock can be slightly metamorphosed and yet retain most characteristics of the original rock. Only the rocks that are obviously metamorphic are included here.

Gneiss: Coarse grained, light colored, with bands of darker minerals (biotite, amphiboles, or pyroxenes) or obvious parallel orientation of darker minerals. Commonly contains quartz, feldspars, micas, plus other minerals in small amounts.

Schist: Generally mica-rich (black biotite, white muscovite, or green chlorite), but also contains quartz, feldspars, and other minerals. Large, parallel mica crystals common.

Slate: Fine grained, breaks in flat pieces generally *across* bedding, which may be visible. Commonly green or black. Can be confused with shale but is harder. Has a slight "ring" to it if held by fingertips and struck with a nail.

Quartzite: Resembles quartz sandstone but is very hard. Grains cannot be loosened. Very glassy, but original quartz sand grains generally visible. Any color.

Marble: Even grained. Cleavage faces of calcite crystals easily visible. Commonly white, but can be gray, pink, or banded. Made of calcite or dolomite, will fizz in acid (with or without scratching). Will not scratch glass.

appendix 8 Guide to common fossils

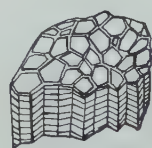
All of the fossils shown are examples of invertebrate animals commonly preserved in sedimentary rocks. There are other, less common types. No microscopic fossils are shown. With the possible exception of some snails and clams, if you find any like those drawn, they lived in the sea.

Corals
(Paleozoic to Present)

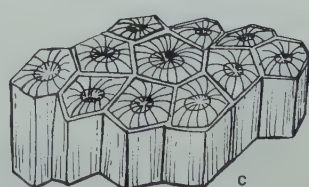
a is a solitary coral shell. One animal lived inside.

b and **c** are pieces of coral colonies. Each "room" was home for an individual. Some types (**a** and **c**) had "room dividers" to help strengthen the shell and support the animal.

a



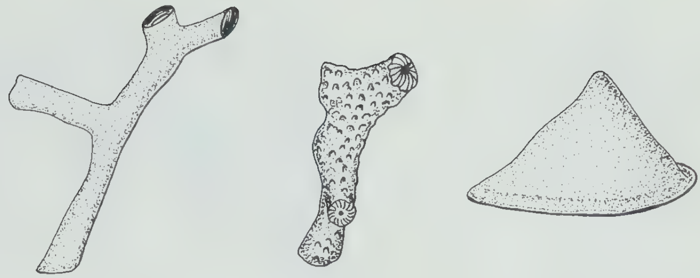
b



c

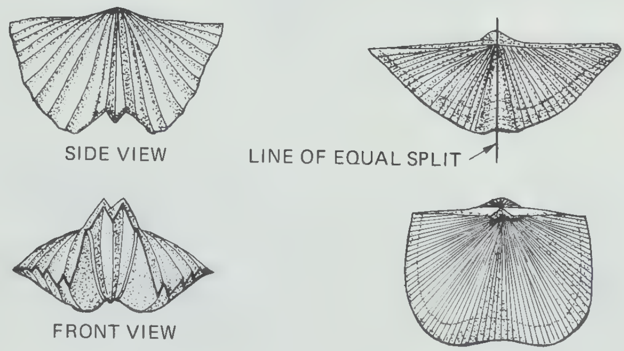
Bryozoa
(Paleozoic to Present)

These "houses" were the homes of many very small individuals. The openings to the "rooms" appear as tiny holes. Some look like branches of trees, others like conical hats.



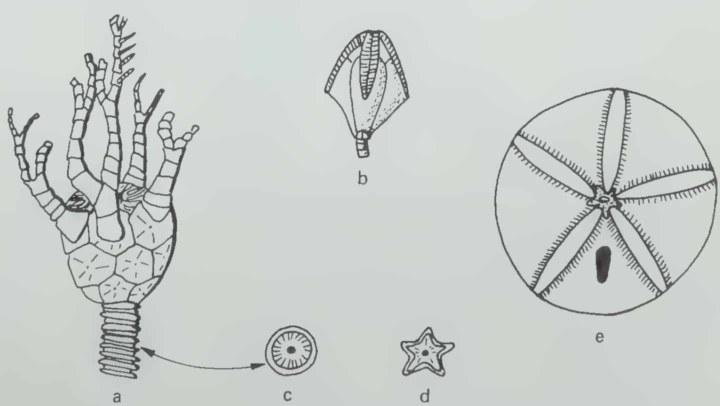
Brachiopods
(Paleozoic to Present)

These animals were very common on Paleozoic sea bottoms. Their shells are in two parts, each valve different from the other. They can be confused with clams. If you split a brachiopod shell (in your mind, if it's someone else's) *through* the valves, each half will be the same shape.



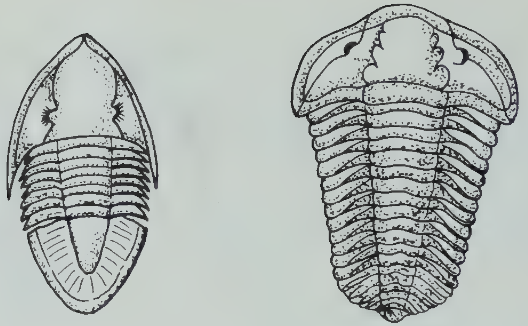
Echinoderms
(Paleozoic to Present)

All of these animals have shells that show some kind of 5-part structure. **a** and **b** were common in the upper Paleozoic. They were often attached to the sea floor by a stem. The platelike pieces of their stems (**c** and **d**) are commonly found. **e** is an unattached wandering type. Sand dollars, sea urchins, and starfish are common modern echinoderms.



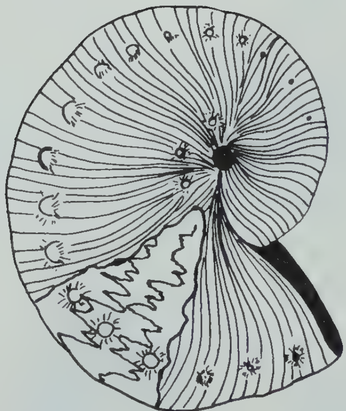
Trilobites
(Paleozoic only)

Extinct for over 200 million years, trilobites are the earliest common fossil. They are related to modern animals such as crabs and insects. Some were only a centimeter long, while others were as long as this page.

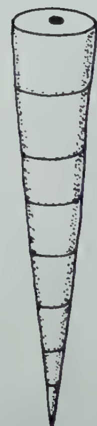


Cephalopods
(Paleozoic to Present)

These shells were lived in by animals related to octopuses and squids. Shelled ones are rare in today's oceans. The shells can be coiled or straight. The coiled ones could be confused with some snails, but the cephalopod shell is divided into separate rooms inside. The animal lived in the last room, and those behind were filled with air after he outgrew each one. On some Mesozoic shells very irregular lines (**a**) can be seen if the thin outer layer is sanded off. Other forms have straight lines (**b**).



a

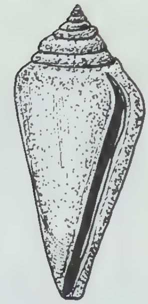


b

Snails (Gastropods)
(Paleozoic to Present)

Snail shells are commonly collected by people who live near the seashore. As the animal grows, more shell is added alongside the opening. The open living area spirals all the way back to the top where the baby snail began making its shell.

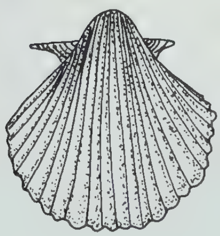
HALF-SIZE



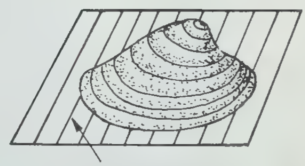
Clams and snails
(Pelecypods)
(Paleozoic to Present)

These shells have two parts. The two valves of clams are nearly alike; so if they are divided *between* the valves, each valve will be nearly the same shape. Even **a**, if cut *through* the valves, would not have like parts. An oyster (**b**) may have one valve attached to rocks, or may lie on its side. The valves grow unequally.

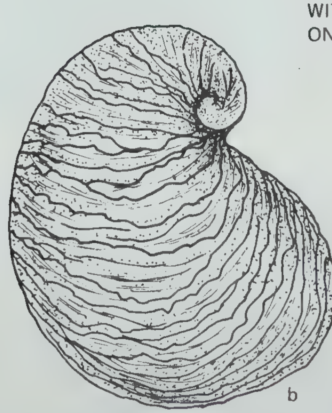
Plane between valves dividing clam into two similar parts. Compare with "line of equal split" on drawing of brachiopod.



a



PLANE BETWEEN VALUES DIVIDING CLAM INTO TWO SIMILAR PARTS. COMPARE WITH "LINE OF EQUAL SPLIT" ON DRAWING OF BRACHIOPOD.



b

appendix 9 Contour lines

A contour line on a map is a line connecting all points of equal height. Figure 1 shows a model of a hill in a fish tank. Imagine that you fill the tank to a height of, say, one centimeter. Mark the water level all around the hill with a pencil. Keep filling the tank in one-centimeter steps and mark the water level. When you are finished, pour off the water and look vertically down at the hill. What you see would look like Figure 2. The lines are contour lines. A more complicated landscape is shown at the top of Figure 3. A map of that landscape is at the bottom. As you can see, the steeper the slope, the closer together the contour lines are. A contour line crossing a river or gulley forms a V pointing up the slope.

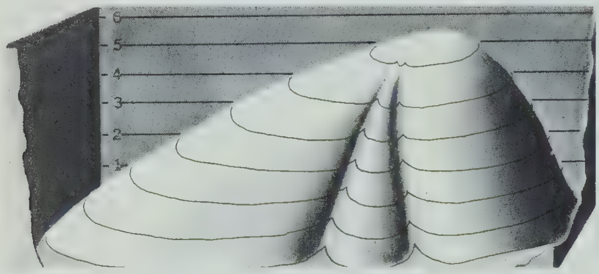


Figure 1

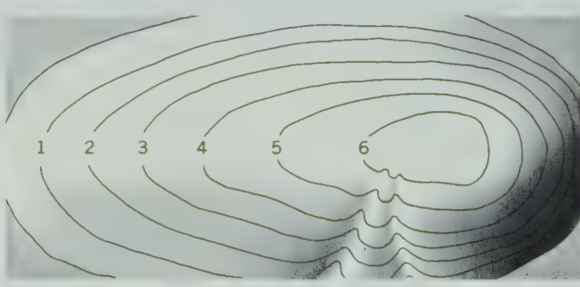
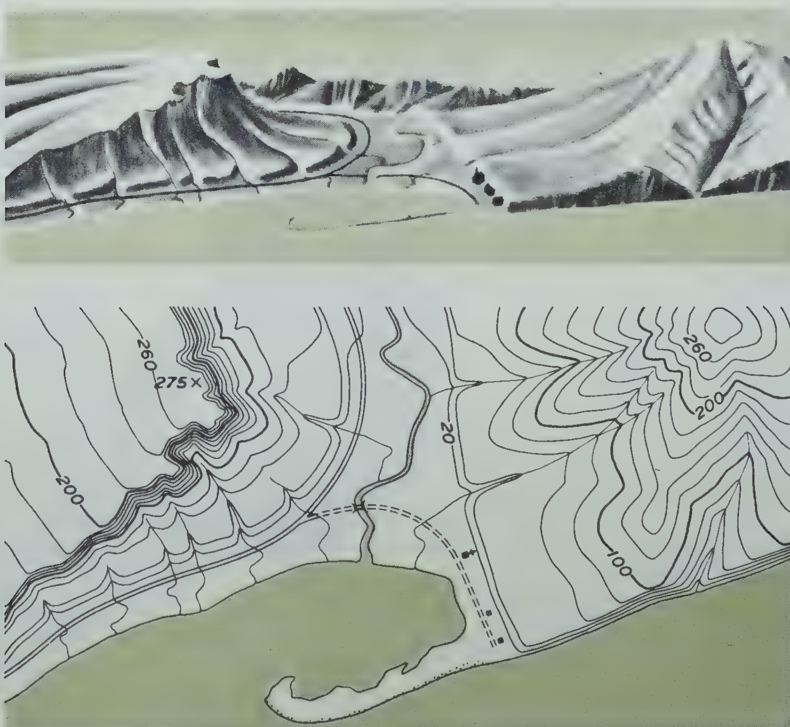


Figure 2

Figure 3



appendix 10 Earth's grid

The points where Earth's axis of rotation intersects Earth's surface are the *North Pole* and the *South Pole*. The circle halfway between them is the *equator*. Positions north or south of the equator are indicated by degrees of latitude, from 0° latitude for the equator to 90°N latitude for the North Pole and 90°S latitude for the South Pole. Each degree of latitude forms a circle that is parallel to the equator and is called a *parallel*. Lines running directly north and south between the two Poles are called *meridians*. The meridian that passes through Greenwich, England is called the *prime meridian*. Positions east or west of the prime meridian are indicated by degrees of longitude, starting from the prime meridian, which is 0° longitude, and going east and west to the meridian exactly opposite the prime meridian; that meridian is 180° longitude.

appendix 11 The seasons

Earth's axis of rotation is not perpendicular to the plane of Earth's rotation around the Sun. It is tilted from the vertical by about $23\frac{1}{2}$ degrees. At left in Figure 1, the North Pole is tilted most toward the Sun; it is midsummer in the Northern Hemisphere and midwinter in the Southern Hemisphere. At right, the North Pole is tilted the most away from the Sun; it is midwinter in the Northern Hemisphere and midsummer in the Southern Hemisphere. Imagine yourself standing at various latitudes as Earth makes a complete rotation. You can see that in summer, daytime is longer than night; and in winter, night is longer than day. At the top and bottom of Figure 1, the line between day and night intersects the Poles. At these two times (called the *spring equinox* and the *autumn equinox*), day and night are the same length on Earth.

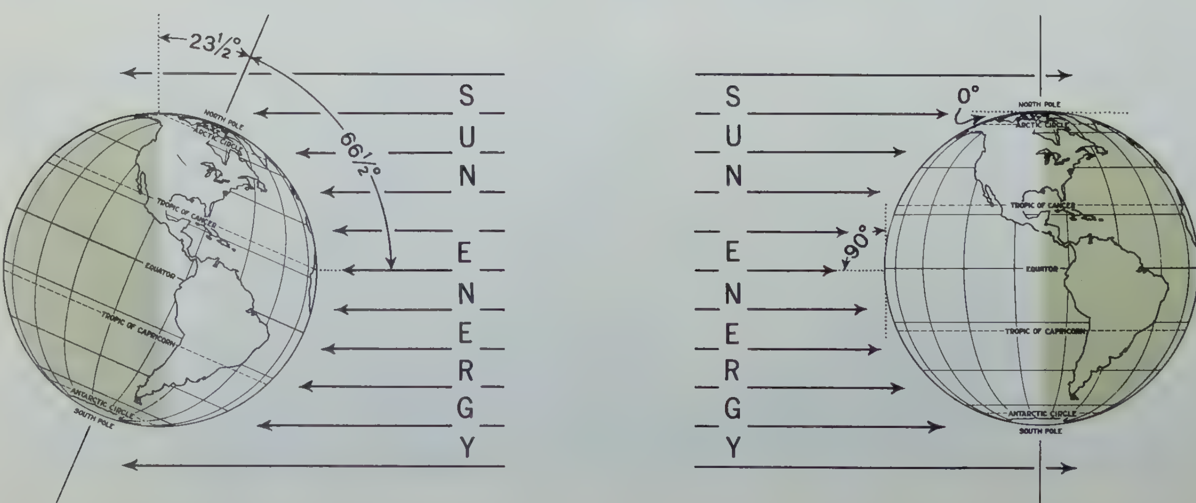
The position of Earth at midsummer for the Northern Hemisphere is shown in more detail in the left part of Figure 2. At that time (June 21 or 22), a person at latitude $22\frac{1}{2}$°N would see the Sun directly overhead at noon. That latitude is called the *tropic of Cancer*. At higher latitudes (for example, the United States), the Sun is never directly overhead. (The southernmost latitude at which the Sun is ever seen directly overhead, $22\frac{1}{2}$°S, is called the *tropic of Capricorn*.) At latitude $66\frac{1}{2}$°S on the day shown at left in

Figure 1

Figure 2, the Sun can be seen only at noon, at which time it is on the horizon. That latitude is called the *antarctic circle.* At latitude $66\frac{1}{2}°$N on that day, the Sun can be seen all day, even at midnight, at which time it is on the horizon. The latitude is called the *arctic circle.*

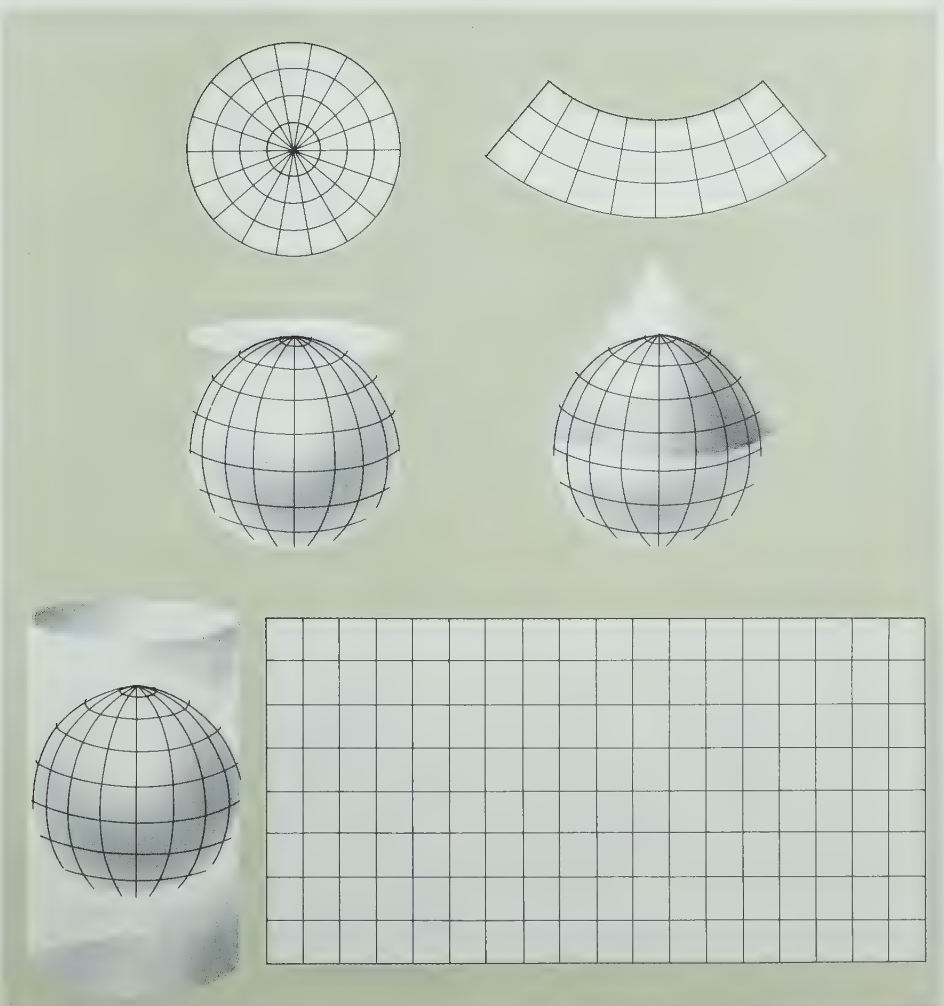
Earth at the time of the equinoxes is shown at right in Figure 2. At both Poles, the Sun is on the horizon all day long. (It moves in a circle around the horizon.) At the equator, on those days, the Sun is directly overhead at noon.

Figure 2



appendix 12 Map projections

Three common methods of projecting the curved surface of a globe on a flat plane are shown in the diagram. In the *azimuthal projection*, (upper left) the plane touches the globe at one point, usually the North Pole or the South Pole. A light inside the globe projects the surface onto the plane. This projection is commonly used for maps of polar areas. In the *conical projection* (upper right), a cone is placed on the globe. (Usually, the apex of the cone lies on the globe's axis, as in the case shown here.) After the globe's surface has been projected onto the cone, the cone is cut to obtain a flat plane. This projection is commonly used for maps of middle-latitude areas, such as the United States. In the *cylindrical projection*, a cylinder is wrapped around the globe, usually touching the globe along the equator. The Poles cannot be shown, since the light inside the globe projects the Poles out to infinity along the globe's axis. This projection is commonly used for world maps, even though it produces bad distortion away from the equatorial area. (The Mercator projection is a well-known cylindrical projection.) Actual maps are constructed not with lights inside globes, but by geometric and other mathematical means.



appendix 13 Astronomical coordinate systems

When watching the sky at night, it seems that the stars and other celestial bodies are attached to a large sphere surrounding Earth. You know, of course, that such a sphere does not exist, yet astronomers use it to describe directions to and motions of celestial bodies. They call it the celestial sphere.

The celestial sphere, with Earth at its center, is shown in Figure 1. Imagine yourself standing at A. The point directly overhead is the zenith (Z). The point directly below you is the nadir (Na). The great circle halfway between them is the celestial horizon (SENW).

Earth spins eastward on its axis, $p_n p_s$. Since we do not feel the rotation, it seems to us that the celestial sphere turns in the opposite—westerly—direction on its axis, $P_N P_S$. As it does so, it seems to carry the Sun, the Moon, the stars, and other celestial bodies along with it.

The celestial north pole, P_N, is located near Polaris, a medium-bright star. Point N on the horizon, nearest to the North Pole, is called the north point. The south point, S, is located in the opposite part of the sky. As you face north, east (E) is on your right, west (W) on your left. They are exactly halfway between north and south. Circles on the celestial sphere that pass through the zenith and the nadir are called the vertical circles. The easiest way to find Polaris is to draw an imaginary line through the α and β stars of the Great Dipper; then lay off five line segments equal to the distance between the two stars. Polaris is close to the endpoint of the fifth line segment (Figure 2).

We are now prepared to discuss the two most frequently used celestial coordinate systems.

The horizon coordinate system

In this system, the direction to a point is described by the *altitude* and the *azimuth.* The altitude of a point is its angular distance from the celestial horizon measured along the vertical circle. The altitude of the star in Figure 3, for instance, is roughly 40°. What is the altitude of a point on the celestial horizon? Of the zenith? Of a point halfway between the horizon and the zenith?

The azimuth of a point is the length of the celestial horizon measured from the north point eastward to the vertical circle. In Figure 3, the azimuth of the star is approximately 120°. What is the azimuth of the north point? Of the west point? Of the point one third of the way from north to east?

The horizon coordinates of a celestial body vary from place to place. Moreover, they change during the course of a day. This is a serious drawback of the system. To describe the direction to a point by means of them, it is, therefore, necessary to also know from where and when the observation was made. Otherwise, the coordinates are of little value.

Figure 1

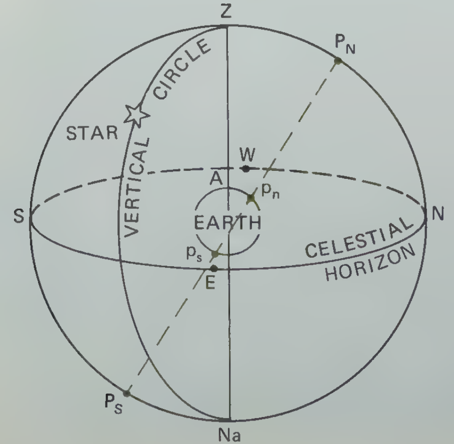
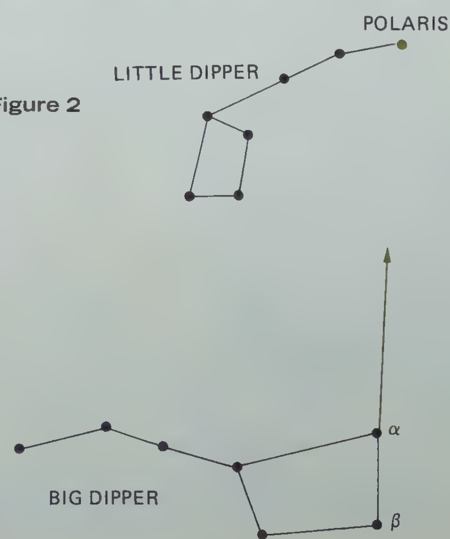


Figure 2



The equator coordinate system

The horizon system measures coordinates from and along the celestial horizon. In the equator system, however, they are measured from and along the celestial equator, the great circle halfway between the two celestial poles.

The equator coordinates are the *declination* and the *right ascension.* To define them, two new ideas must be introduced: (1) Great circles passing through both celestial poles are called the hour circles. An example is P_N-star-P_S in Figure 4. (2) The point on the celestial equator that the Sun reaches at the beginning of spring (around March 21) is referred to as the vernal equinox (γ). Its approximate position can be found from constellation Pegasus (Figure 5).

The declination of a point is its angular distance from the celestial equator measured along the hour circle. The declination of the star in Figure 4, for instance, is +30°, the plus sign meaning that the point is in the northern celestial hemisphere. Declinations of points in the southern hemisphere are indicated by a minus sign. What is the declination of points on the celestial equator? Of the celestial north pole? Of the celestial south pole? Of a star two thirds of its way from the celestial equator to the celestial north pole?

The right ascension of a point is measured leftward along the celestial equator. It is measured in hours, minutes, and seconds. (The celestial equator is divided into 24 hours, as explained in Chapter 17, activity 17.3. The right ascension of the vernal equinox can be designated as either 0 hour or 24 hours.)

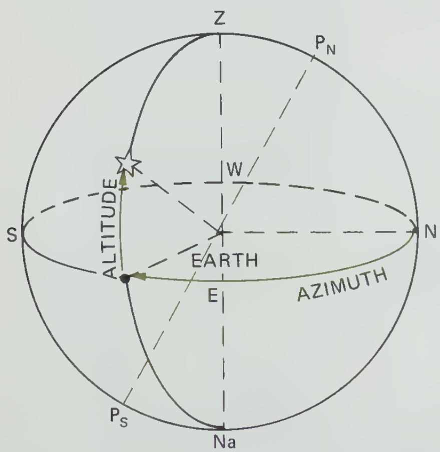
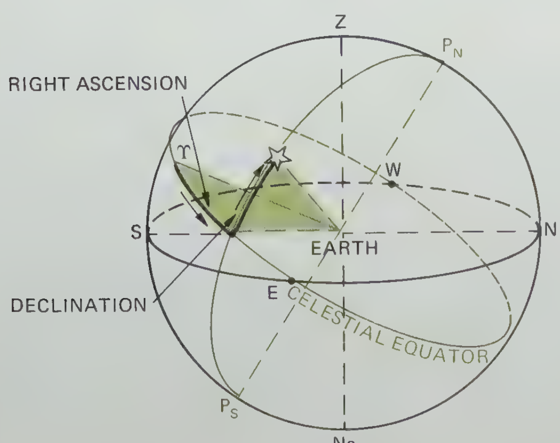


Figure 3

Figure 4



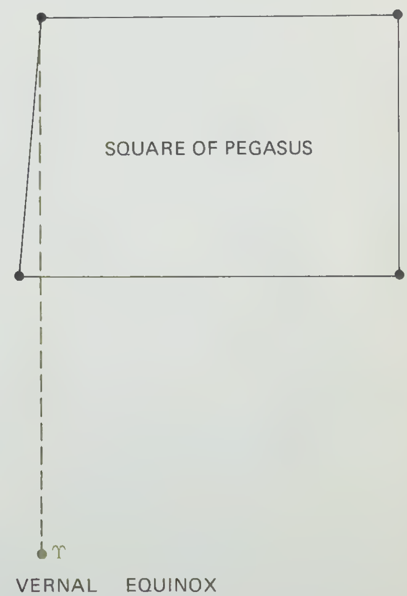
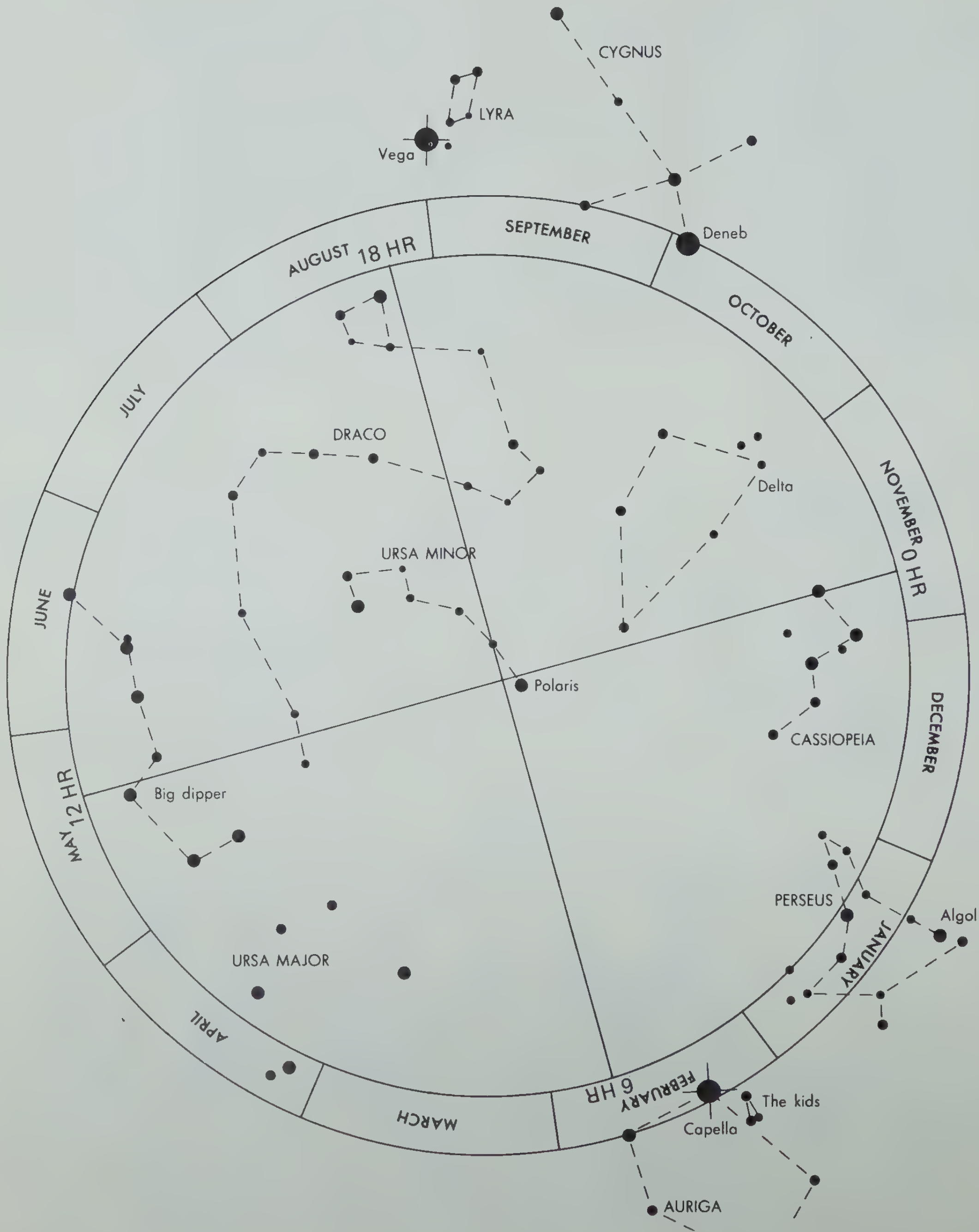


Figure 5

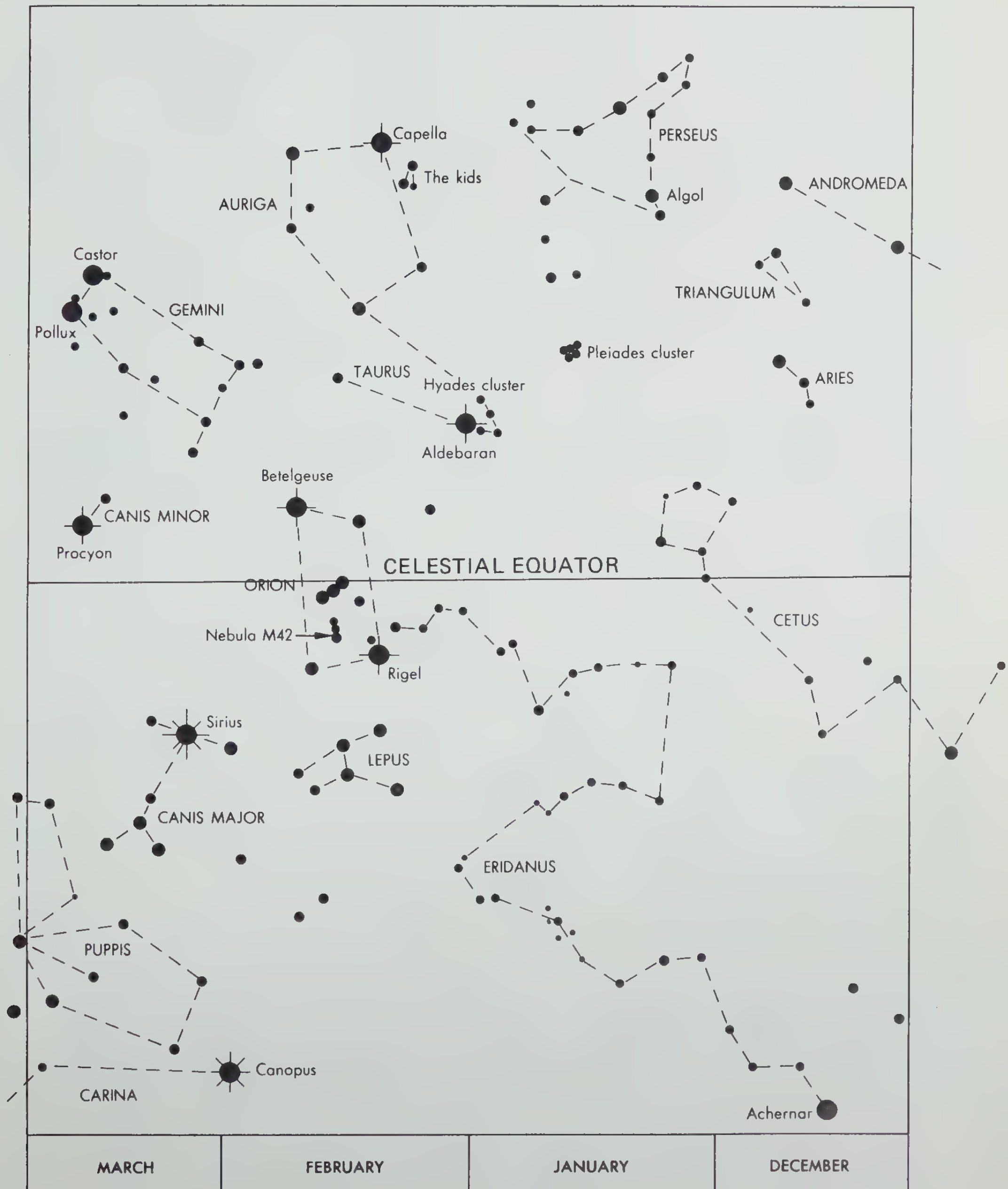
appendix 14 **Star charts**

This circular chart shows the stars near the north celestial pole (the intersection of the two lines). From most of the continental United States, the stars within the circle can be seen all year. To use the chart, go outdoors around 9 pm, face north, and hold the chart in front of you so that the label for the month in which you are doing this activity is located at the top. The chart will correspond to what you see in the



region around the north celestial pole. The stars appear to rotate counterclockwise around the pole. Four right ascension values are shown: 0 (or 24), 6, 12, and 18 hours.

The following rectangular charts cover areas of the sky from the celestial equator to a declination of about 60 degrees north and south. The labels at the bottom indicate the months in which the particular section of the sky can be seen. Hold the chart directly above your head and line up the directions as indicated. (For example, if you stand facing south, the words would appear right side up. If you stand facing north, the words would appear upside down.)

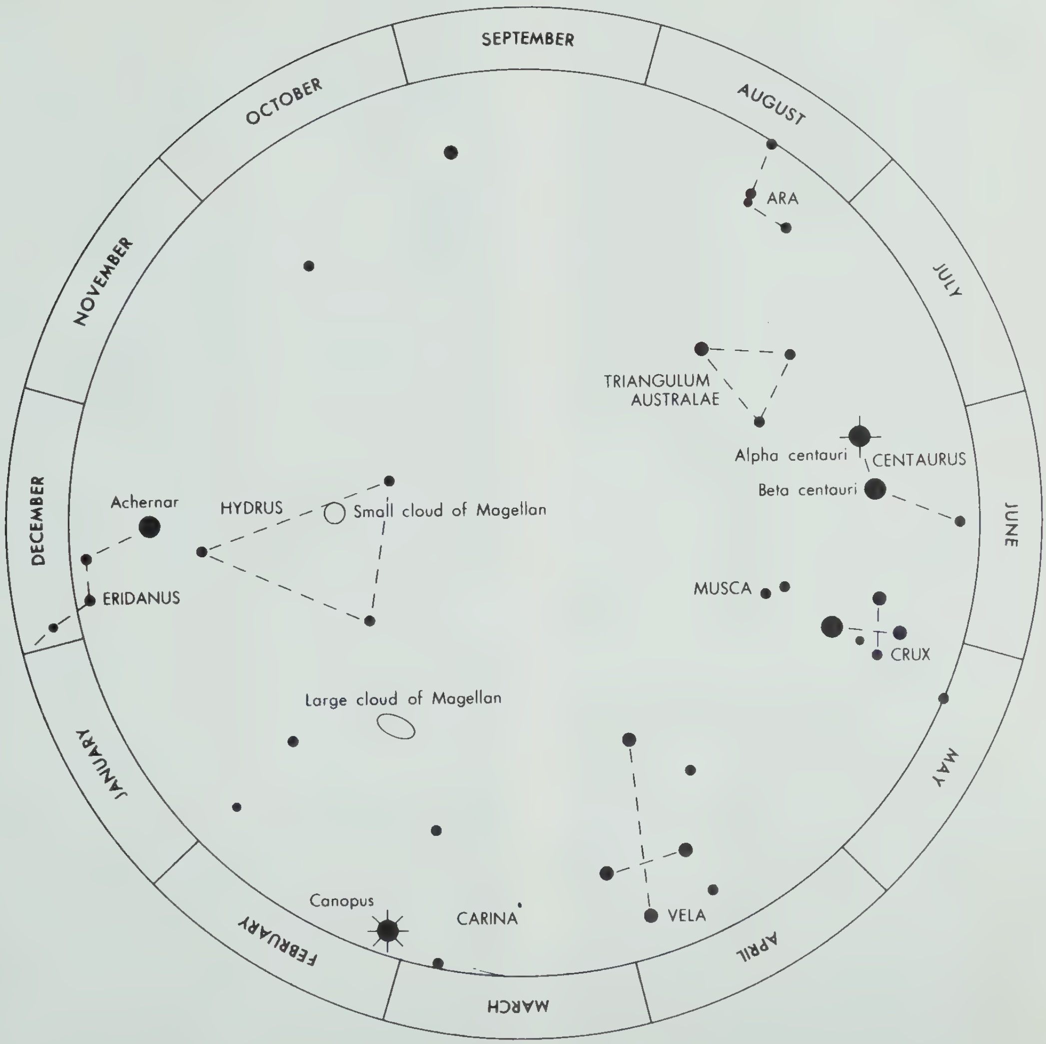


CASSIOPEIA
N
E
W
S
Deneb
Galaxy M31
ANDROMEDA
Vega
TRIANGULUM
CYGNUS
LYRA
ARIES
PEGASUS
SAGITTA
DELPHINUS
Altair
PISCES
CELESTIAL EQUATOR
AQUILA
CETUS
AQUARIUS
CAPRICORNUS
SAGITTARIUS
Fomalhaut
PISCES
AUSTRINUS
GRUS
ERIDANUS
Achernar
DECEMBER
NOVEMBER
OCTOBER
SEPTEMBER


DRACO
URSA MAJOR
Big dipper
N
E
W
S
CYGNUS
LYRA
Vega
Cluster M13
HERCULES
BOOTES
CORONA BOREALIS
Arcturus
SAGITTA
SERPENS
OPHIUCHUS
Altair
CELESTIAL EQUATOR
AQUILA
VIRGO
SERPENS
LIBRA
Spica
HYDRA
Antares
SAGITTARIUS
SCORPIUS
CENTAURUS
ARA
CRUX
Alpha centauri
SEPTEMBER
AUGUST
JULY
JUNE


Big dipper
URSA MAJOR
N
E
W
S
Castor
Pollux
GEMINI
Arcturus
LEO
Bee-hive cluster
CANCER
Regulus
CANIS
MINOR
VIRGO
CELESTIAL EQUATOR
Procyon
Spica
Sirius
CRATER
HYDRA
CORVUS
CANIS MAJOR
PUPPIS
Globular cluster
VELA
CENTAURUS
CRUX
CARINA
Canopus
JUNE
MAY
APRIL
MARCH

STARS AROUND THE SOUTH CELESTIAL POLE



glossary

absorption spectrum *ab SORP shun* The dark lines on the bright background of a continuous spectrum.
abyssal plain *uh BIH sul* Same as deep-sea plain.
active volcano A volcano that has displayed some volcanic activity within the last 50 years or so.
alluvial fan *a LOO vee ul* An accumulation of sediment formed where a stream descends from a steep slope onto a flatter land area and deposits its load of sediment. (The land counterpart of a delta.)
amphibian *am FIB ee uhn* A type of cold-blooded vertebrate animal that normally must keep its skin moist and lay its eggs in water. Frogs and toads are examples.
angstrom *ANG strum* A unit of length, equal to 10^{-10} meter (one ten-millionth of a meter), abbreviated as Å or A.
annual displacement The yearly change in the direction of a star, expressed in angular seconds.
antapex *AN tuh pex* The point in the sky opposite the apex.
anthracite *AN thruh sait* A hard variety of coal, usually with a shiny appearance, formed from the metamorphism of lower grade coal.
anticline *AN tih klain* A structure in which stratified rocks are folded upwards.
apex *AY pex* The point in the constellation Hercules toward which the Sun is moving.
apparent brightness The amount of light received from a star.
arkos *AR kose* A type of sandstone containing an appreciable amount of feldspar grains in addition to abundant quartz grains (see sandstone).
asteroid *AS teh royd* A minor planet or planetoid; many of these lie in an orbit between Mars and Jupiter.
astronomical unit *as troh NOM i kul* An average Earth-Sun distance, 150 million kilometers (93,000,000 miles).
atmosphere (unit of pressure) *AT mos feer* The average pressure of the atmosphere at sea level, equal to about 10^5 newtons per square meter or 14.7 pounds per square inch.
atom The smallest particle of an element having properties of that element; composed of protons, neutrons, electrons, and numerous smaller particles.
atomic number The number of protons in the nucleus of an atom (see electron shell).
avalanche *AV uh lanch* A large mass of snow or ice moving rapidly down a mountain slope.
barred spiral galaxy *SPAI rul GA lax ee* A galaxy in which the arms develop from the endpoints of a "bar" and then coil about it.
basalt flood *ba SALT* A type of volcanic activity in which very fluid basaltic lava poured out of numerous long fissures or cracks and flooded large areas.
basaltic magma *ba SAHL tik* Magma of basaltic composition, high in calcium, iron, and magnesium and relatively low in silicon.
batholith *BA tho lith* A large body of igneous rock that cuts across the structure of the surrounding rocks and doesn't have a known base.
bauxite *BOX ait* The chief ore of aluminum. A mixture of several hydrous aluminum oxides, whose composition is commonly given as $Al_2O_3 \cdot nH_2O$.
binary star *BAI ne ri* One of the two stars revolving about their common center of mass.
black hole A collapsed star having so great a surface gravity that light cannot escape the star.
breccia *BRECH i a* A kind of rock whose parts are angular and appear cemented together.
breeder reactor A nuclear reactor in which certain nonfissionable isotopes can be changed to ones that are fissionable. An example is the change of uranium-238, which is not fissionable, to uranium-233, which is. The reactor thus "breeds" its own fuel supply to produce energy by nuclear fission.
bright-line spectrum (see emission spectrum)
catastrophism *ka TAS tro fism* The concept that geological features are the result of sudden violent changes rather than the result of slow processes acting over long periods of time.
celestial equator *seh LES chul ee KWAY tur* A great circle projected on the sky 90° from the celestial poles. It lies in the same plane as the Earth's equator.
celestial sphere The imaginary sphere that represents the entire sky.
cepheid *SEE fee id* A periodically pulsating yellow supergiant star having a period between a day and several weeks.
chemical weathering The chemical breakdown or decomposition of rocks and minerals at Earth's surface, due to exposure to air and water.
chromosphere *KROH mos feer* The red shell of the solar atmosphere lying directly above the visible surface of the Sun.
cinder cone A cone-shaped mound or hill formed by the accumulation of volcanic ash and cinders around a volcanic vent.
cleavage *KLEE vij* The tendency of a mineral to break along flat, shiny surfaces due to crystalline structure.
climate The weather conditions—including temperature, precipitation, and wind—that are characteristic of an area or region.
cluster of galaxies A group of galaxies held together by their mutual gravitational force.
cold front The surface between a cold and a warm air mass formed when the cold air pushes beneath the warm air and lifts it up.
comet head The diffuse gaseous component of the comet; the most dense region of the comet.

comet tail The whispy vaporous extension of some comets; these point away from the Sun as the comet passes by.
composite cone *kom PAH zit* A large volcanic cone made up of layers of lava and pyroclastic material.
composition The chemical makeup of a rock or mineral.
compound A substance composed of two or more different elements.
compression A process in which forces acting toward each other squeeze or compress rocks.
conglomerate *kon GLAH mer it* Sedimentary rock containing a large proportion of rounded gravel and pebbles (larger than 2 mm in diameter).
contact metamorphism Metamorphism of surrounding rocks caused by the intrusion or extrusion of magma.
continental drift The movement of continents over the surface of the Earth.
continental glacier A large ice sheet that covers a large part of a continent (see glacier).
continental rise The gently-sloping surface of the sea floor lying at the base of the continental slope.
continental sea A type of sea which covered various parts of continents many times in the past. Most areas of these seas were only a few hundreds of meters deep.
continuous spectrum An uninterrupted band of rainbow colors obtained when the light from a glowing solid, liquid, or highly compressed gas is dispersed by a glass prism or a grating.
convection cell *kun VEK shun* A pair of convection currents adjacent to each other and moving in opposite directions. (The convection currents make up a closed circulation of material.) Such a slow movement of material in the mantle due to temperature differences (with the hot currents rising and cold currents falling) may account for continental drift.
core The innermost zone of Earth, starting at a depth of about 2900 km beneath the surface. It has a liquid outer part and a solid inner part, both composed of iron and nickel.
Coriolis effect *koh ree OH lis* An effect caused by Earth's rotation, in which particles moving in the Northern Hemisphere veer to the right and in the Southern Hemisphere veer to the left.
corona *ko ROH nuh* The outer part of the solar atmosphere.
correlation *ko reh LAY shun* The process of matching rocks between two or more areas. Position relative to other rocks, fossils, and type of rock are among the things used to correlate. If two rocks correlate, they are considered to be of nearly the same age.
covalent bond *koh VAY lent* A linkage between atoms in which the atoms share electrons.
cross-beds Thinner sedimentary beds or laminations within a main bed, which are inclined at an angle to the main bed.
crust The outermost shell of the solid Earth. It varies in thickness from about 5 km under the oceans to 60 km under continents.
crystal lattice (see crystal structure) A specific and periodic arrangement of atoms which distinguishes crystalline solids from other states of matter.
crystal structure (see crystal lattice) The orderly arrangement of atoms in a crystal.
crystalline *KRIS ta lin* Having a regular and orderly atomic structure, as contrasted with amorphous materials which have no crystalline structure.
dark-line spectrum (see absorption spectrum)
deep-sea plain The smooth flat floor of the ocean occurring in depths greater than 2000 meters.
deep-sea trench Long linear depressions on the sea floor characterized by volcanic and intense earthquake activity.
delta *DEL tuh* A low-lying accumulation of sediment formed where a stream flows into a body of standing water and deposits its load of sediment.
deposition *dee poh ZIH shun* The laying down of sediment by water, wind, or ice.
dike A rock body formed as an offshoot from a body of magma, shaped like a wall and cutting across the layers of surrounding rock.
dinosaur *DAI nuh sawr* A common name given to two groups of reptiles that were the dominant land vertebrates during Mesozoic time. Some were very small, others the largest land animals ever. The name comes from the Greek words *deinos* (terrible or mighty) and *sauros* (lizard).
doldrums *DOL drumz* (also called equatorial low and intertropical convergence zone) The area near the equator characterized by low pressure and a lack of steady winds.
dome mountain A mountain in which the rocks have been pushed up into a dome by forces within Earth.
Doppler effect *DOP lur* The apparent change in the wavelength of sound, light, or other radiation brought about by the motion of the source along the line of sight.
dormant volcano *DOR munt* A volcano which has not been active within the last 50 years or so.
drainage basin The area from which a given stream and its tributaries receive their water.
echo sounder A device used to measure water depth; it measures the time a pulse of sound takes to travel to the bottom and back to the device.
eclipse *ee KLIPS* The cutting off of all or part of the light from one celestial body by the passing of another in front of it.
eclogite *EH kloh jait* A rock with the chemical composition of a basalt, but with different mineral composition, which occurs near the base of Earth's crust.
electromagnetic waves Waves produced by oscillating electric and magnetic fields.
electron *ee LEK trahn* Negatively charged particle

in an atom, in orbit around the nucleus.
electron shell An imaginary spherical surface representing all possible paths of electrons with the same average distance from a nucleus.
element A substance which cannot be broken down into other substances by ordinary chemical means; a substance made completely of atoms with the same atomic number.
ellipse *ee LIPS* A flattened circle; the orbits of all celestial bodies are ellipses.
elliptical galaxy *ee LIP tih kl* An armless galaxy that has elliptical contours and that displays no spiral structure.
emission spectrum A spectrum made up of bright lines on a dark background.
equatorial low (see doldrums)
erosion *ee ROH zhun* The wearing away of Earth's surface by wind, water, and ice.
erosion cycle The concept which states that valleys and landscapes progress through youthful, mature, and old age stages of erosion, with each stage recognizable by the erosional features present.
extension A process in which forces acting away from each other cause a stretching of rocks.
extinct volcano *ek STINKT* A volcano which has not been active in recorded history.
extrusive rock *ex TROO siv* (see volcanic rock)
fault *FALLT* A break in Earth's crust along which there has been vertical and/or horizontal movement.
fault-block mountain A mountain which has one or more faults along its margins and was formed by movement along the fault.
flare A short-lived brilliant eruption on the Sun.
folded mountain range A mountain range in which stratified rocks, deposited in a geosyncline, are folded into mountain ranges. Rocks in such mountains are commonly folded, faulted, metamorphosed, and intruded.
foliated *FOH lee ay tid* The layered or banded nature of some metamorphic rocks, caused by pressure being strongest in a certain direction.
footwall The wall of a nonvertical fault that would be underfoot if a person were standing in a tunnel dug along the fault.
fossil *FAH sul* Any remains or trace of a once-living thing preserved by natural means.
fracture zone A long linear zone on the sea floor characterized by long steep escarpments, ridges, troughs, and/or lines of seamounts.
frontal surface The surface between a cold air mass and a warm air mass.
full moon The phase of the Moon when its side facing the Earth is fully illuminated.
galaxy An assemblage of millions or billions of stars, gas, and dust in space.
geologic time scale A calendar of Earth history.
geosyncline *jee oh SIN klain* A long, narrow, subsiding basin in which thick accumulations of sediment occur.
glacial till *GLAY shul* An accumulation of nonsorted and unstratified sediment carried and deposited by a glacier.
glacier *GLAY shur* (see continental glacier and valley glacier) A moving mass of ice which originates from the compacting of snow by pressure.
graded (bed) A sedimentary bed in which the coarsest grains are at the bottom and the finer grains at the top, with a progression of grain sizes within it.
granitic magma *gra NIH tik* Magma of granitic composition, high in silicon, sodium, and potassium and relatively low in calcium, iron, and magnesium.
granitization *gra nih tih ZAY shun* The changing of some other type of rock into granite by solutions moving through the rock.
granule *GRAN ewl* A short-lived bright area on the surface of the Sun a few hundred kilometers in diameter.
gravitational force A force of attraction existing between any two bodies.
gravity *GRA vih tee* The force on any body of matter at or near Earth's surface due to the attraction by Earth, and to its rotation about its axis.
graywacke *GRAY wak* A type of sandstone which is dark and hard and composed of angular mineral and rock particles set in a clayey matrix (see sandstone).
greenhouse effect The trapping, by the atmosphere, of electromagnetic waves whose wavelengths are longer than those of visible light.
gyre *JAIR* A circular motion; in the oceans, the circular paths followed by the major ocean currents, clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.
half life The time it takes for one-half of the atoms of any given quantity of a radioactive form of an element to decay to atoms of another element.
halite *HA lite* A mineral composed of the elements sodium and chlorine; rock salt and common table salt are halite.
hanging wall The wall of a nonvertical fault that would be overhead if a person were standing in a tunnel dug along the fault.
hematite *HEH muh tait* The mineral FE_2O_3, the principal ore of iron.
high tide The high level of ocean water on the side of Earth facing the Moon and on the opposite side.
humus *HYOO mus* A dark-colored, well-decomposed part of the organic material in soils.
hydrothermal solution *hai dro THER mul* A hot watery solution derived from magmas.
igneous (rocks) *IG nee us* Rocks formed by the crystallization of magma, either at depth or at Earth's surface.

intertropical convergence zone (see doldrums)
intrusive rock *in TROO siv* (see plutonic rock)
invertebrate *in VER ti brayt* A general term for animals which do not have a backbone. Insects, worms, and clams are examples.
ion *EYE ahn* A charged atom, produced by the gain or loss of electrons.
ionic bond A linkage between two charged atoms (ions), the result of their opposite electrical charges.
ionosphere *eye ON os feer* A thick zone in the outer atmosphere in which the atmospheric faces become ionized by incoming solar radiation.
irregular galaxy An irregularly-shaped galaxy without arms.
isobar *EYE soh bar* A line on a pressure-pattern map that connects points of equal pressure.
isohyet *eye soh HAI et* A line on a precipitation map that connects points of equal precipitation.
isostasy *eye SOS tuh see* The balance that would be achieved by the different segments of Earth's crust with their different densities if gravity were the only force that affected their heights in relation to one another. The blocks are "in balance" with one another.
isotherm *EYE so thurm* A line on a temperature pattern that connects points of equal temperature.
isotope *EYE soh tohp* Any one of two or more forms of an element which differ in the number of neutrons in the nucleus. Only the weight of the element varies; its chemical activity remains about the same as its other isotopes. Naturally-occurring elements are usually mixtures of isotopes. For example, over 99.7% of the oxygen you are breathing has 16 neutrons in the nucleus, but about 0.2% has 18 neutrons.
jet stream A fast, narrow stream of air flowing along a winding path in a generally west-to-east direction at altitudes of 10 to 12 kilometers. The jet stream transports a great deal of heat from the tropics to the polar regions.
landslide A mass of soil and rock which falls or slides rapidly down a slope.
lava *LAH va* Magma which has poured out on Earth's surface; also used for the rock which has solidified from this magma.
leveling The process in which topographically high areas are lowered and low places are filled in. Involves weathering, erosion, and deposition.
light-year The distance covered by light in one year.
limestone A sedimentary rock composed largely of the mineral calcite.
lobe fin A type of fin found in some ancient and a few modern fish in which the fins are fleshy and supported by bones and muscles which are connected to the internal skeleton. This type of fin is related to the legs of other vertebrate animals.
Local Group The cluster of 19 or possibly more galaxies which includes the Milky Way system.
low tide The low level of ocean water on the two sides of Earth between the high tide areas.
luminosity *lew mih NAH si tee* The rate of light emitted by a celestial body.
lunar eclipse An eclipse of the Moon, when the Earth passes between the Moon and the Sun.
magma *MAG ma* Molten rock; magma consists of complex silicate melt, gases, and solid crystals.
magmatic differentiation *mag MA tik di feh ren shee AY shun* The process whereby different types of magma and igneous rocks are formed from a single parent magma.
magnetite *MAG nih tait* The mineral Fe_3O_4, an ore of iron. It is magnetic.
main sequence A diagonal, narrow band in the Hertzsprung-Russell diagram within which most of the nearby stars are located.
mammal *MAM ul* A type of warm-blooded vertebrate animal that has hair and feeds its young with mother's milk.
mantle *MAN tl* The zone of Earth beneath the crust and above the core. Its top is between 5 and 60 km from the surface. Its base is about 2900 km down.
marble A metamorphic rock formed from limestone or dolomite, and hence composed of the mineral calcite or dolomite or both. It has a granular texture.
massive bed A homogeneous sedimentary bed without noticeable lamination, cross-bedding, grading, or other sedimentary features.
mechanical weathering The physical breakdown of rocks and minerals at Earth's surface into smaller pieces.
meltwater deposit An accumulation of sorted and stratified sediment deposited by the water resulting from a melting glacier.
mesosphere *MEH sos feer* The third layer of the atmosphere found above the stratosphere (50 km) and extending up to 80 km. The temperature decreases to $-90°$ C.
metamorphic (rocks) *me ta MOR fik* Rocks formed at depth from other pre-existing rocks, the result of pronounced changes in temperature, pressure, and chemical environment.
metamorphism *me tuh MORF izm* The process by which the physical and/or chemical properties of a rock are changed under conditions of temperature, pressure, and chemical environment different from those in which the rock was formed. The effects of weathering and cementation are not usually included.
meteor *MEE tee r* The streak of light observed when a meteroid enters the Earth's atmosphere and burns up; popularly called a "shooting star."
meteorite *MEE tee r ait* A portion of a meteoroid that survives passage through the atmosphere and strikes the Earth.
meteor shower Many meteors appearing to radiate

from a common point in the sky; caused by the collision of the Earth with a swarm of meteoritic particles.
meteroid *MEE tee r oid* A particle in space before an encounter with the Earth.
micrometeoroid The very smallest meteoroid.
mineral A naturally occurring, inorganic, crystalline, relatively homogeneous substance with definite chemical and physical properties.
Mohole project *MOH hole* A scientific project designed to drill a hole through the Mohorovičić discontinuity into the uppermost part of the mantle.
Mohorovičić discontinuity *mo ho ROH vih chich dis kon tih NEW i tee* The boundary between the crust and the mantle of Earth. This is the most studied boundary or discontinuity between layers.
moraine *moh RAYN* A kind of land form composed of glacial till (see glacial till).
mountain Any part of Earth's surface that rises high above surrounding areas.
mud cracks Polygonal cracks in mud formed by the drying up and contraction of wet mud at Earth's surface.
mudstone Sedimentary rock largely composed of clay, commonly with much silt, as well; breaks into irregular blocks (see shale).
multiple star One of two or more mutually revolving stars.
nebula *NEH bew la* A cloud of gas and dust in interstellar space.
neutron *NEW trahn* A particle in the nucleus of an atom with no electrical charge, but with a mass about equal to that of a proton.
neutron star A very high density star made up of electrically neutral particles called neutrons.
new moon Phase of the Moon when it lies between the Earth and the Sun.
normal fault A fault in which the hanging wall has moved down *relative* to the footwall.
normal spiral galaxy A spiral galaxy in which the arms wind out of the galactic nucleus.
nova *NOH vuh* A star that blows off its outer layer in a sudden outburst increasing hundreds of thousands of times in luminosity.
nuclear fission *NEW klee ur FISH un* The splitting of the nucleus of an atom into two new nuclei. A large amount of energy is given off when this occurs.
nuclear fusion *NEW klee ur FEW shun* The combining of two smaller nuclei to form a larger one. A large amount of energy is given off when this occurs. Sometimes this process is referred to as a thermonuclear reaction, since very high temperatures are required to start it.
nucleus *NEW klee us* The central part of an atom, containing the protons and neutrons, and therefore most of the mass but only a small part of the volume.
oxidation *ox ih DAY shun* The process of combining with oxygen.
P wave An earthquake wave that moves with a push-pull action. A P wave is the same as a primary wave.
parallax *PAH ruh lax* The change in the direction of an object when viewed from two different points.
periodotite *PEH ri doh tait* A dark-colored, coarse-grained, igneous rock composed mostly of iron and magnesium-rich minerals such as olivine and pyroxene.
phase Any one of the progression of changes in the Moon's appearance during a month.
photosynthesis *fo to SIN thi sis* A process by which plants produce glucose from carbon dioxide and water by using light energy with chlorophyll present.
phytoplankton *fai to PLANK tun* Microscopic floating plants which live in the ocean's surface waters.
pillowed lava flow A flow that has rounded pillow-like structures developed in it. These structures are developed when lava is extruded under water.
placer gold Native gold which is naturally sorted by streams because of its high specific gravity.
plain A large, fairly level area.
plateau *pla TOH* A high, flat area usually underlain by nearly horizontal layered rocks. Relief on plateaus is commonly greater than on plains.
plutonic rock *ploo TAH nik* Rock formed beneath Earth's surface by the solidification of magma.
polar zone One of the regions of Earth where the average temperature of the warmest month does not reach as high as 10° C (50° F).
primate *PRAI mayt* A type of mammal that usually has long limbs, enlarged "hands" and "feet" with either or both toe and thumb opposable to four other digits, nails rather than claws, forward-directed eyes, and the most highly developed nervous system and intelligence. Monkeys, apes, and humans are examples.
principle of uniformity A basic assumption needed to understand the general nature of all things. It assumes that the basic components of matter and the laws of science are the same everywhere.
principle of superposition *soo pur puh ZIH shun* The principle that a layer of sedimentary rock that overlies another is younger. The positions will not change from one area to another unless the rocks have been faulted or overturned by a fold.
prominence *PROH mih nence* A rapidly changing formation of glowing gases above the solar limb.
proton *PROH tahn* A positively charged particle in the nucleus of an atom. Protons have more than 1800 times as much mass as electrons.
Proxima Centauri *PROX ih muh sen TAU ree* The star (other than the Sun) nearest to Earth. It is 4.28 light-years away.
pulsar *PUL sar* A star emitting regular short radio "bursts" (pulses).
pyroclastic particle *pai ro KLAS tik* A rock, mineral, or glass particle that has been thrown out of a volcanic vent.

quarter moon Either of the two phases of the Moon when the angle between the Earth, Moon, and Sun is 90°.
quartz sandstone *KWARTZ* A type of sandstone composed largely of quartz grains (see sandstone).
quasar *KWAY zar* A starlike celestial body having a very high red shift; its true nature is not yet understood.
radial motion The motion of a star directly toward or away from us.
radioactive If some form of an element has the property of emitting (radiating) certain rays (gamma) and particles (electrons, for example), it is said to be radioactive.
ray fin A type of fin found on most ancient and nearly all modern fish in which the fins are webs of skin supported by rays of "horny" material.
red shift The displacement of the dark lines toward the red end in the spectra of many heavenly bodies.
regional metamorphism Metamorphism over broad areas, brought about by great pressures and temperatures. It is most common in regions of mountain building.
reptile *REP tail* A type of cold-blooded vertebrate animal that usually lays a shelled egg and has a scaly skin. Snakes and alligators are examples.
respiration *reh spih RAY shun* The intake by living organisms of oxygen to maintain life processes and the output of waste products.
reverse fault A fault in which the hanging wall has moved up *relative* to the footwall.
Richter scale *RIK ter* A scale scientists use to describe the amout of energy released by an earthquake. The scale runs from 1 to 10. The biggest earthquake ever recorded had a value of 8.6 on the Richter scale.
rift valley A linear valley caused by separation along a fault in the Earth's crust; common at the centers of mid-ocean ridges.
ripple marks An irregular wavy surface produced in loose sediment by wind or water.
rock cycle Concept of the sequences through which earth materials may pass when subjected to geological processes.
RR Lyrae variable *LAI ree* A pulsating white giant star having a period of less than a day.
S wave An earthquake wave which advanced by causing particles in its path to move from side to side or up and down at right angles.
salinity *sah LIN i tee* A measure of the salt content of water. Seawater has a salinity of about 3.5% by weight.
sand dune A mound or ridge of sand piled and deposited by wind.
sandstone Sedimentary rock largely composed of sand-sized particles (between 1/16 and 2 mm in diameter).
sea-floor spreading A theory which explains the movement of continents as a result of the addition of new crust at mid-ocean ridges with a movement of the sea floor away from the ridges.
seamount A mountain or hill on the sea floor which rises 1000 m or more above its surroundings.
sediment *SEH di ment* Loose unconsolidated particles of minerals and rocks.
sedimentary facies *FAY sees* Lateral changes in the type of sediment or sedimentary rock from place to place within a sedimentary rock unit.
sedimentary (rocks) *se di MEN teri* Rocks formed at Earth's surface, made from particles of other rocks or precipitated out of solution with or without the aid of organisms.
seismogram *SAIZ muh gram* A graph or chart recorded on a seismograph.
seismograph *SAIZ muh graf* An instrument for recording vibrations, most commonly Earth vibrations.
shale Sedimentary rock largely composed of silt and clay-sized particles; breaks into thin flat pieces (see mudstone).
sheetwash Thin sheets of water moving down a slope during and after a rain.
shield Any extensive area, usually low-lying, over which Precambrian age rocks are exposed at the surface.
shield volcano A large, broad, low volcano made up of lava flows.
silicate (minerals) *SIL ih kayt* Minerals containing silicon-oxygen tetrahedrons.
sill A rock body formed as an offshoot from a body of magma into a flat space between layers of surrounding rock.
siltstone Sedimentary rock largely composed of silt-sized particles (between 1/16 and 1/256 mm in diameter).
slate *SLAYT* A fine-grained metamorphic rock with well-developed slaty cleavage, formed by the metamorphism of mud, stone, or shale.
solar easterlies Winds flowing from the polar areas of high pressure.
solar eclipse An eclipse of the Sun, when the Moon passes between the Earth and the Sun.
solar flare (see flare)
specific gravity The density of a substance compared to the density of an equal volume of pure water.
spectroscope *SPEK troh skohp* An instrument used to separate light into its component wavelengths (colors).
spectroscopy *spek TRO sko pee* The study of electromagnetic waves and their various wavelengths.
spectrum *SPEK trum* (see absorption spectrum, continuous spectrum, and emission spectrum)
spiral galaxy A flattened galaxy with spiral arms emerging from its nucleus.
stationary front A frontal surface (between a cold air mass and a warm air mass) that does not move noticeably.
strata *STRAY ta* (sing. **stratum**) Layers or beds of sedimentary rock.

stratosphere *STRA tos feer* A stable layer of the atmosphere immediately above the troposphere (12.5 km) and extending up to the mesosphere (50 km). The temperature increases slowly with altitude from −57° C to 0° C.
submarine canyon A large steep-walled submarine valley.
submarine valley A sea floor feature similar in form and size to river valleys on land.
subsurface water mass A mass of seawater having generally the same chemical and physical characteristics and behaving as a unit beneath the ocean's surface.
subtropical high Area of high atmospheric pressure at about latitude 30° north or south.
sunspot A transient dark area on the solar disk brought about by a temporary decrease in temperature.
supercluster of galaxies A group of two or more clusters of galaxies.
supergiant An extremely luminous and large star.
supernova A brilliant explosion of a star during the course of which the star ejects about a half of its mass into space.
surface wave An earthquake wave that moves along the surface of Earth rather than through it. Surface waves cause most of the earthquake damage.
syncline *SIN klain* A structure in stratified rocks in which rocks are downfolded. The opposite of an anticline.
taconite *TAH kuh nait* A very hard, iron-bearing, silica-rich sedimentary rock formation. The iron content is low (25–35%).
temperate zone *TEM per it* One of the regions of Earth between the polar zones and the tropical zone.
tetrahedron *teh tra HEE drun* The common 4-sided geometric form assumed by 4 oxygen ions and one silicon ion.
texture Geometrical aspects of the particles within a rock, including size, shape, and arrangement.
thermosphere *THUR mos feer* The fourth layer of the atmosphere found above the mesosphere (80 km) and reaching up to an indefinite 400 km. Temperatures increase rapidly from −90° C to 1100° C.
topsoil The top layer of soil, rich in humus and clay minerals.
trade winds The winds from the Northern and Southern Hemispheres converging at the equator.
trilobite *TRAI luh bait* An extinct Paleozoic animal distantly related to modern crabs, insects, and other jointed-legged invertebrate animals. Trilobites are the earliest fossils commonly found on Earth.
tropical zone The region of Earth where the average temperature of the coolest month does not drop below 18° C (65° F).
troposphere *TROH pos feer* The lowest zone of the atmosphere; it is typified by a relatively regular decrease of temperature with altitude. The portion of the atmosphere where weather takes place; its thickness is about 12.5 km.
turbidity current *tur BIH di tee* A highly turbid (muddy) and dense current which moves along the bottom slope of a standing body of water.
uniformitarianism *yu ni for mi TEH ri uh ni zm* The concept that the present is the key to the past.
upwelling The upward movement of ocean water, primarily in coastal areas, in response to the offshore movement of surface water by wind.
valley glacier A glacier occupying a valley, usually in mountains (see glacier).
vertebrate *VER ti brayt* A general term for animals which have some type of internal backbone for support. Frogs, snakes, and elephants are examples.
volcanic rock *vol KA nik* Rock formed at Earth's surface by the solidification of lava.
warm front The surface between a warm and a cold air mass formed when the warm air advances over the cold air.
water cycle The general pattern of movement of water from the sea by evaporation into the atmosphere, then by precipitation onto the land, and then by the pull of gravity back to the sea.
water table The upper surface of accumulation of underground water. It is highest beneath hills and lowest beneath valleys.
weather The conditions of the atmosphere at a given time and place.
weathering (see chemical weathering and mechanical weathering)
westerlies Winds that blow toward the subtropical high belts from the poleward side.
white dwarf A small star of very high density and temperature but low luminosity.

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